THE DEVELOPMENT OF SPINAL DEFORMITY IN EXPERIMENTAL SCOLIOSIS

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THE DEVELOPMENT OF SPINAL DEFORMITY IN EXPERIMENTAL SCOLIOSIS

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Helsinki, February 1965

Jarl Erik Michelsson

I INTRODUCTION
PURPOSE OF THE INVESTIGATION

In 1957 LINDEMANN stated that BIESALSKI was right in calling scoliosis the old *crux orthopaedica*. He based his opinion on the fact that the development of this condition has remained obscure although the most eminent specialists have been trying for two-hundred years to solve its problem. In spite of the progress made in the research on scoliosis, particularly during the last decades about 90 per cent of cases must be described as idiopathic according to COBB.

The methods available for the treatment of scoliosis are unsatisfactory. There is no reliable therapy to prevent the progression of an idiopathic scoliosis and opinions differ concerning the usefulness of operative measures (HIRSCH). Spinal fusion is generally regarded as the best operation although usually only partial correction has been achieved (JAMES, MAU, PONSETI).

PONSETI has stated that the problem of idiopathic scoliosis cannot be regarded as solved until the nature of the disease has been clarified and the causative deficiency can be corrected. »In all other fields within the scope of surgery it is by experiment that a decision as to the correct form of therapy has been reached. It is to be hoped that the study of scoliosis may also reap some benefit from work of this kind« (ARND).

Although the problem of scoliosis has been the object of many experimental investigations, the initiating mechanism of provoked scoliosis has not been subjected to closer study.

For several years A. LANGENSKIÖLD and I have made systematic and unbiassed experiments on rabbits and pigs in order to clarify the pathogenesis of scoliosis and if possible find a basis for new methods of therapy. This work has been performed in part by both of us, in part by myself. Our previous results have been published in two papers »Experimental Progressive Scoliosis in the Rabbit« (1961) and »The Pathogenesis of Experimental Progressive Scoliosis« (1962). In these we described various operations which

frequently led to progressive and severe structural scoliosis. The operations most effectively inducing scoliosis were resection of the dorsal ends of ribs and hemilaminectomy. A factor which these operations had in common was the resection of posterior costotransverse ligaments. In both rabbits and pigs transection of these ligaments alone sometimes led to progressive scoliosis of the same type as is seen in man. It is known that the costotransverse ligaments play an important part in transmitting normal muscle tone to the spine. These structures seem to be necessary for both the maintenance of the equilibrium and the symmetrical growth of the spine.

The purpose of the present study was to investigate the initiating mechanism and the evolution of the change of various structures in experimental scoliosis.

II SURVEY OF THE LITERATURE

»In no other type of deformity is there encountered such a magnitude of intricate and baffling problems as one is confronted with in scoliosis. This is a condition that has spurred speculation and investigation to a remarkable degree, and the great web of literature woven around the subject might well dismay even the most assiduous of readers». These words were written by MICHELE in 1963.

Different theories concerning the pathology, aetiology, pathogenesis and therapy of scoliosis have been thoroughly described in Handbuch der Orthopädie, Band II, 1958.

A. Certain features of the pathology of human scoliosis

Classification. From the standpoint of aetiology and pathogenesis scoliosis can be classified as myopathic, osteopathic, neuropathic or idiopathic. The last mentioned group is by far the largest (COBB). Clinically a distinction can be made between functional and structural scoliosis. In functional scoliosis there are no permanent adaptive changes of the spine and spontaneous straightening is possible, while the structural form is characterized by adaptive deformities of bones and soft parts and spontaneous straightening can no longer take place (KLEINBERG, LOVETT, MICHELE).

Pathological changes. In structural scoliosis the lateral deviation is associated with rotation of certain vertebrae in the curve, except in pleural scoliosis (BISGARD). Mostly there is one primary curve and this is usually associated with one or more compensatory curves. In structural scoliosis the curves are rigid (KLEINBERG). The commonest site of the primary curve is the caudal part of the thoracic spine, and in about 80 per cent of cases the convexity is directed to the right (SHANDS & EISBERG). Structural changes

occur in both the spine and its vicinity. The severest vertebral changes are found at the apices of the curves. Rib hump is a common finding in thoracic scoliosis (JENTSCHURA, KLEINBERG).

B. Vertebral growth in man and animals

The growth of the human vertebrae is not fully understood, but it is generally accepted that the vertebral body grows in length by means of plates of epiphyseal cartilage on the cranial and caudal surfaces (BICK & COPEL, BISGARD & MUSSELMAN, COVENTRY & al., SCHMORL).

During growth the cranial and caudal surfaces of the human vertebral body exhibit a ring-shaped structure, the apophysis, by SCHMORL called »Randleiste». Animals, e.g. the rabbit and the pig, have a disc-shaped epiphyseal nucleus corresponding to the epiphyseal ring (BEADLE, PACHECO, SMITH & WALMSLEY). The vertebral apophyses do not essentially participate in the longitudinal growth of the vertebral bodies (BICK & COPEL).

In mammals as well as in man longitudinal growth of the vertebral bodies takes place at the epiphyseal plates (BEADLE, BISGARD & MUSSELMAN, PACHECO, STILWELL).

C. Earlier experimental studies on scoliosis

Before A. LANGENSKIÖLD and I started our studies many experimental investigations had been performed in order to induce scoliosis in laboratory animals, but they had not always been systematic, and in most cases only slight or no scoliosis had resulted.

1. *Transection or excision of muscles alone.* In addition to various groups of dorsal muscles, the following muscles have been either excised or transected alone: the trapezius, the latissimus dorsi, the sacrospinalis, the pectoralis, the iliopsoas, the scaleni, abdominal muscles, the psoas major and intercostal muscles. As a rule, however, only slight or no scoliosis has been [illegible] (ARND, CAREY, FREY, MARCONI, MILES, PLAGEMANN, PUSCH[illegible]ZMANN & MILES, SOMERVILLE, STILWELL).

Transection or excision of muscles and ligaments at the dorsolumbar level. [illegible] resection of one or both sacrospinal muscles and interspinous and flaval ligaments (STILWELL) has induced kyphosis or scoliosis.

3 *Denervation of muscles* Transection of the phrenic intercostal or various spinal nerve has occasionally led to slight scoliosis (BISGARD FREY LESSER MARCONI MILES)

4 *Rib resection* has been performed in various ways scoliosis has resulted only in certain cases (BISGARD DRACHTER HUETER PLAGEMANN) Rib resection in conjunction with fixation of contralateral ribs has produced slight scoliosis (FREY)

5 *Fixation of the spine* in an abnormal position has been performed by attaching the tail to the scapular region (MATTLOKA MAU MULLER RIBBERT UNGER WULLSTEIN) or by fixing it in plaster (PLAGEMANN) or with metal (PAP) Occasionally scoliosis or kyphosis has been induced In some cases slight scoliosis has been obtained by the *fixation of ribs or transverse processes* (FREY PITZEN) Severe scoliosis (lordosis and rotation) has resulted from the *fixation of spinous processes* alone (GOTTLIEB et al) and in conjunction with cauterization of vertebral arches (SOMERVILLE)

6 *Operations on vertebrae* Resection of transverse processes has sometimes led to slight scoliosis (PLAGEMANN VAVRDA) while cauterization of arches has failed to induce this condition (SOMERVILLE) Resection or stapling of the cranial or caudal growth zones of vertebral bodies has usually led to scoliosis with the concavity towards the operated side (BISGARD & MUSSELMAN GHILLINI HAAS MOSER NACHLAS & BORDEN) and damage to the neurocentral junction on one side has resulted in slight scoliosis (OTTANDER) Resection of both epiphyses of vertebral bodies and neurocentral junctions has provoked slight scoliosis (PACHER) Furthermore this condition has been induced by hemilaminectomy in conjunction with transection of spinal nerves in the lumbar region (TROUPP)

7 *Radiation* with X rays or radium has sometimes resulted in scoliosis (ARKIN & SIMON ENGEL ENGEL & RICHTER)

8 *Other methods* Sometimes scoliosis has resulted from various kinds of pleural damage (BISGARD) experimentally induced lathyrism (AMATO & BOMBELLI DURAISWAMI DURIEZ et al PONSETI PONSETI & BAIRD PONSETI & SHEPHARD) oxygen deficiency (DEGENHARDT RUTT & GRUETER) renal damage (BLUMENSAAT) unilateral labyrinthine ablation (DE KLEYN & BRAND MAGNUS) abnormal labyrinthine stimulation (POOS & WALTER) disarticulation of an extremity (V FRISCH) provoked luxation of the hip or pseudoarthrosis of the femur (FREY)

Our own earlier experimental investigations have been described in two papers mentioned on page 9

III MATERIAL AND METHODS

A Laboratory animals

The present study is based on the results of operations on 800 growing rabbits and 66 growing pigs. These numbers include the animals on which our previous studies were performed. The rabbits were operated on at the age of six to eighty days, the pigs at the age of fourteen to sixty days.

B General operative technique

Anaesthesia. The rabbits were operated on under local anaesthesia (0.25 per cent Xylocain without evadrine) and the pigs under deep general anaesthesia using Trilene.

Extent and location of the operations. As a rule, the operations on both rabbits and pigs were made at the levels of five vertebrae or corresponding ribs. The thoracic operations on rabbits were performed in the caudal region of the thoracic spine, mostly at the sixth to tenth thoracic vertebrae or the corresponding ribs, and the lumbar operations were made at the first to fifth lumbar vertebrae (the rabbit has seven lumbar vertebrae). On the pigs only thoracic operations were performed, as a rule at the seventh to eleventh thoracic vertebrae (the pig has thirteen to sixteen thoracic vertebrae). The operations were usually performed unilaterally and on the right side, since in the majority of cases human scoliosis is right convex (SHANDS & EISBERG). For the sake of comparison unilateral operations were also performed on the left side, but the results corresponded to those obtained after operations on the right side.

Surgical approach. As a rule, a dorsal longitudinal midline incision in the skin was made [illegible] te of the operation, parts of the trapezius and the latissimus dorsi [illegible] d from spinous processes, when necessary, and at

the deeper operations the sacrospinalis and the other deep back muscles were also freed from spinous processes and arches In some cases the operation was performed between the different parts of the sacrospinalis or laterally *of this muscle*

Operative complications At the more extensive operations pneumothorax was a common complication but its effect on the position of the spine was negligible At hemilaminectomy spinal nerves were sometimes injured Fatal haemorrhages were rare and mortality during or immediately following the operations was relatively low

Antibiotics Immediately after operation most rabbits were given an injection of penicillin and the pigs were given penicillin and streptomycin intramuscularly for some days after operation Occasionally antibiotics were applied locally during the operation The frequency of postoperative infection and the mortality were somewhat lower in the animals given antibiotics than in the remainder

C Methods of selective resection, transection transposition or electrocoagulation of structures in the spine or its vicinity

Generally speaking corresponding structures occur in the spine and its vicinity in man the pig and the rabbit (EILENBERGER & BAUM KRAUSE)

The role of various structures in maintaining the position of the spine was studied by resection transection transposition or electrocoagulation of different muscles ligaments nerves and/or bones The different operations are listed in Table I They were all performed on rabbits but only some were performed on pig In the majority of cases the operation was unilaterally performed as a rule at five levels and involved only one kind of structure These operations are here called »simple» In some cases operations involving more than one kind of structure (»combined operations») were performed either on the same side or on both sides of the spine see page 28

D Methods of fixing different parts of the skeleton to each other

On growing rabbits and pigs various parts of the skeleton (spinous processes transverse processes and/or ribs) were unilaterally fixed to each other with nylon thread Depending on the size of the animal, one or more

Table I — *Operations performed for the purpose of testing their possible effect on the growing spine*

All operations were unilaterally performed as a rule at five levels
+ Scoliosis usually resulted
± Persistent structural scoliosis sometimes resulted
— Scoliosis only occasionally resulted
Oper. no. indicates the order in which the different operations were taken into use

(See text on page 15)

Oper. no.	Operation	Rabbits			Pigs		
		No of animals	Funct scoliosis	Struct scoliosis	No of animals	Funct scoliosis	Struct scoliosis
	A OPERATIONS ON MUSCLES AND/OR LIGAMENTS						
	I *Transection or resection of muscles and/or ligaments*						
I A	Resection of the sacrospinalis	21	—	—			
I B	Resection of all muscles attached to the spinous processes and the arches	10	—	—			
VII	Resection of the transversocostal muscles	13	—	—			
XXXI	Transection of the intertransverse ligaments	3	—	—			
XXVII	Transection of the costotransverse ligaments	59	+	±	7	+	+
XIX	Transection of the ligaments of the tubercles of the ribs	3	—	—			
XVIII	Transection of the ligaments of the heads of the ribs	38	+	+			
XX	Transection of the ligaments attached to the dorsal ends of the ribs	17	+	+	2	+	+
XXV	Transection of the intercostal muscles	9	+	±	3	+	+
XXVII	Transection of all muscles and ligaments between the transverse processes and between the arches in the lumbar spine	8	+	+			
XXXII	Transection of the iliopsoas	1	—	—			
XXXIII	Transection of the gluteus medius	1	—	—			

Oper no	Operation	Rabbit			Pig		
		No of animal	Funct scoliosis	Struct scoliosis	No of animals	Funct scoliosis	Struct scoliosis
	Transposition of muscles						
XIII	Transposition of the rhomboid muscles to ribs on the same side	4	–	–			
XIV	Transposition of the rhomboid muscles to contralateral rib			–			
XV	Transposition of the rhomboid muscles and the trapezius to contralateral ribs	6	–	–			
	B OPERATIONS ON NERVES						
III	Transection of the intercostal nerve	13	+	±			
XII	Transection of the phrenic nerve	6	–	–			
	C OPERATIONS ON BONES						
XXIV	Hemilaminectomy in the thoracic spine	6	+	+		±	±
XXIV	Hemilaminectomy in the lumbar spine	3	+	+			
XXIX	Transvertebrectomy in the thoracic spine	7	+	±			
XXIX	Transvertebrectomy in the lumbar spine		+	+			
XVII	Resection of the heads of the rib	14	+	+	1	+	+
XXI	Provoked epiphysiolysis of the heads of the rib or transection of the necks of the rib	16	+	±			
VI	Resection of the dorsal ends of the ribs	1	+	+	1	+	+
X	Transection of the ribs laterally of their tubercle	9	–	–			
II	Transection of the thoracic wall lateral to the tubercles of the rib	8	+	+			
Xa	*Resection of the ribs laterally of their tubercles*	5	+	+			
XI	Electrocoagulation of the ventral growth zones of the ribs	3	–				
XXVI	Resection of the ventral growth zones of the ribs	4	–	–			

nylon threads were tied around the parts to be fixed In addition to unilateral fixation of ribs transection of certain structures on the other side was performed on some rabbits The fixative operations and their results are described in detail on page 19

E Methods of investigation

Both living animals and specimens were studied *by ocular inspection* Furthermore, photographs were taken when indicated

Radiological investigation The position of the spine was radiologically recorded in all animals The first radiographs were taken immediately after operation in the case of most of the rabbits and some pigs Subsequently radiographs were usually taken at short intervals as long as the animal survived and often also post mortem In many cases the animal was dissected and radiographs of the specimens were taken When radiographs were taken in the anteroposterior projection, for technical reasons the animals were usually kept in the dorsal position For the sake of comparison radiographs were also taken with the living animal lying as freely as possible face down or standing on its legs but the position of the spine was in these cases more or less the same as when the animal was kept on its back Lateral views were also taken but not in all cases

Measurement of the degree of scoliosis (lateral deviation of the primary curve of the spine) was performed by COBB s method On radiographs intersecting perpendiculars were drawn from the superior surface of the cranial vertebra and the inferior surface of the caudal vertebra of the curve The complementary angle indicated the degree of scoliosis Absolute values for the lateral deviation of the spine cannot be obtained by this or any other method (JENTSCHURA KLEINBERG) Changes of less than 10 degrees in the lateral deviation of the spine were therefore as a rule not taken into account in this study

Measurement of different parts of vertebrae was performed with calipers

Marking of growing vertebrae was performed with vitallium screws on some pigs in order to study the growth changes in scoliosis

Histological investigation A number of rabbit vertebrae were histologically investigated After fixation in neutral formalin and decalcination in EDTA (ethylenediaminetetra acetic acid) the specimens were embedded in paraffin sectioned in the frontal or transverse planes and stained with haematoxylin VAN GIESON

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IV RESULTS

A The immediate effect of different operations on the position of the spine

Immediately after the different surgical procedures (see Table I page 20) the position of the spine was radiologically recorded in the anteroposterior projection in the majority of rabbits and some pigs As appears in Table I no lateral deviation of the spine resulted from 14 of the 29 different operations while 15 operations usually led to initial scoliosis which could also be called functional since no adaptive structural changes had yet developed The results of the operations inducing scoliosis are described in detail on page 20

After the following unilateral operations neither initial (functional) nor later structural scoliosis developed

Resection of the deep back muscles in the thoracic region

Transposition of various back muscles

Transection of intertransverse ligaments

Transection of the ligaments of the tubercles of ribs

Transection of muscles in the hip region (the iliopsoas and gluteal muscles)

Transection of the phrenic nerve

Partial hemilaminectomy (not including the articular processes) in the thoracic spine

Transection of ribs at a site far laterally of their tubercles

Resection or electrocoagulation of the ventral ends of ribs

Usually no appreciable initial scoliosis developed immediately after operations in which various skeletal parts were fixed to each other with nylon thread The results of these operations are described in detail on page 49

B The functional scoliosis developing immediately after operation

Provocation of functional scoliosis in rabbits by operation on a single kind of stabilizing structure

Fifteen of the 29 operations listed in Table I, performed on different structures in the spine or its vicinity, immediately led to scoliosis which was convex to the side of the operation All these procedures involved either resection or transection of muscles, ligaments nerves and/or bones The results of the operations provoking scoliosis are compiled in Table II The table shows that the scoliosis induced by the different operations varied in degree Wide variations in degree al o occurred after the same operation This may be due to variations in the operative technique to the non stationary character of scoliosis the depth of the anaesthesia and the general condition of the animal at the examination etc Even though no absolute conclusions concerning the quantitative effect of the different operations under taken in order to induce scoliosis can be drawn from the present studies, certain tendencies are discernible Fig 1 a—h illustrate functional scoliosis after different operations

Resection of the dorsal ends of ribs led to the severest functional scoliosis encountered in the present study When rib resection was done laterally of the tubercles of the ribs the resulting scoliosis was usually much slighter The more laterally the resection was performed and the smaller the pieces resected the slighter was the scoliosis provoked When *transection of the ribs and intercostal nerves and vessels* was done laterally of the tubercles of the ribs the resulting scoliosis was as a rule relatively slight

Resection or provoked epiphysiolysis of the heads of ribs or *transection of the ligaments of the heads of ribs* usually resulted in rather severe scolio is

Transection of both external and internal intercostal muscles led to relatively severe scoliosis The effect on the position of the spine of the different parts of the intercostal mu cles is described on page 26

Hemilaminectomy in the thoracic spine provoked scoliosis which depended on the extent of the operation The more laterally the removal of bone was extended the severer was the resulting scoliosis The most radical operations involved re ection of the arch from the base of the spinous proce s to the ba e of the transverse proces

TABLE II — *Functional scoliosis in rabbits which developed immediately after resection or transection of different structures in the spine or its vicinity*

All operations were performed unilaterally at five levels

Operation	Scoliosis in degree			No. of rabbits
	Average	Min	Max	
Thoracic operations				
Resection of the dorsal ends of the ribs including both costal joint surfaces	51	25	87	125
Resection of the heads of the ribs	51	35	69	14
Provoked epiphysiolysis of the heads of the ribs or resection of the necks of the ribs	51	33	65	16
Transection of the ligaments of the head of the rib	49	7	80	38
Transection of the intercostal muscles	49	28	70	9
Transection of the anterior and posterior costotransverse ligament	44	18	78	59
Hemilaminectomy	44	20	70	56
Transection of the ligaments attached to the dorsal ends of the ribs	38	5	60	17
Transection of the intercostal nerve	37	15	55	13
Resection of the ribs laterally of their tubercle	55	15	75	25
Transection of the thoracic wall	21	0	45	8
Transversectomy	18	0	4	
Lumbar operations				
Transection of all muscles and ligaments between the transverse processes and between the spines and the arches	40	15	70	8
Transversectomy	3	0	6	2
Hemilaminectomy	17	0	35	9
			Total	406

Transection of the costotransverse ligaments alone resulted in scoliosis which was on the average equally severe as that induced by hemilaminectomy. It should be borne in mind that when hemilaminectomy was radically performed the posterior costotransverse ligament was also resected.

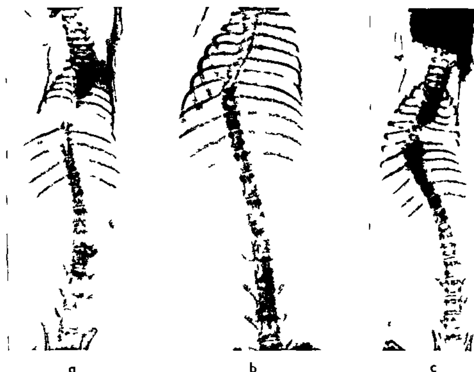


Fig. 1. Rabbit. Initial scoliosis immediately resulting from eight different operations involving different structures in the spine or its vicinity. The operations were performed unilaterally on the right side at five levels. *a* Transsection of the costotransverse ligament. *b* Hemilaminectomy. *c* Transection of the ligament of the head of the rib. *d* Transection of the neck of the rib. *e* Resection of the head of the rib. *f* Transection of the ligament attached to the dorsal end of the rib. *g* Transection of the intercostal muscle. *h* Resection of the dorsal end of the rib.

Transection of all ligaments attaching the dorsal ends of ribs to the spine provoked scoliosis which was somewhat slighter than that resulting from the majority of the other scoliosis-provoking operations on this part of the rib.

Transection of intercostal nerves led to moderate and *transversectomy in the thoracic spine* to slight scoliosis.

Of the operations performed on the lumbar spine transection of all muscles and ligaments attached to arches and transverse processes led to much severer scoliosis than *transversectomy* or *hemilaminectomy*.


d


e


f


g


h

Dependence of the scoliosis on the extent of the operation

In order to study the relationship between initial scoliosis and the extent of the operation one and the same procedure was unilaterally performed but at different numbers of levels and both on different animals and on one and the same animal step by step though in one sequence After each operative phase the position of the spine was immediately radiologically recorded

Transection of the costotransverse ligaments was done on 5 rabbits of the same litter at different numbers of levels The results are shown in Table III

TABLE III — *Immediate results of transection of the costotransverse ligaments performed unilaterally at different numbers of levels in 5 rabbits of the same litter*

Rabbit no	Location of operation	Scoliosis in degrees
518	Th 6	7
519	Th 6 — Th 7	20
520	Th 6 — Th 8	35
521	Th 6 — Th 9	4[illegible]
524	Th 6 — Th 10	50

The same operation was performed step by step on 3 rabbits from the sixth to tenth thoracic vertebrae The results are seen in Table IV and are illustrated in Fig 2

TABLE IV — *Immediate results in 3 rabbits of transection of the costotransverse ligament performed unilaterally step by step in one sequence at different numbers of levels*

Location of operation	Average scoliosis in degrees
Th 6	1[illegible]
Th 6 — Th 7	19
Th 6 — Th 8	[illegible]
Th 6 — Th 9	3[illegible]
Th 6 — Th 10	40

III. Rabbit. Transection of the costotransverse ligaments on the right side step by step in one sequence. The position of the spine was radiographically [illegible] after each operative phase. Transection performed [illegible] Th [illegible] 8–11 c [illegible] 7 c Th [illegible] 8 d Th 6–[illegible] and e Th 6–10

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Rabbit no	Location of operation	Scoliosis in degree
518	Th 6	7
519	Th 6 — Th 7	0
5[illegible]0	Th 6 — Th 8	35
521	Th 6 — Th 9	42
5[illegible]4	Th 6 — Th 10	50

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TABLE IV — *Immediate results in 3 rabbits of transection of the costotransverse ligament performed unilaterally step by step in one sequence at different numbers of levels*

Location of operation	Average scoliosis in degree
Th 6	12
Th 6 — Th 7	19
Th 6 — Th 8	28
Th 6 — Th 9	37
Th 6 — Th [illegible]	40

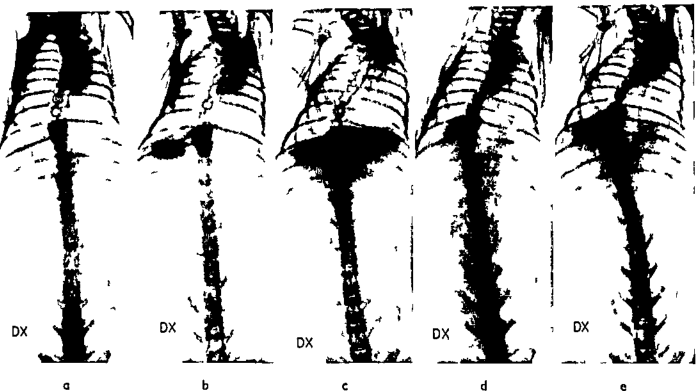


Fig. [illegible] Rabbit. Transection of the costo-transverse ligaments on the right side step by step in one sequence. The position of the spine recorded radiographically immediately after each operative phase. Transection performed by *a* Th 6, *b* Th 6–7, *c* Th 6–8, *d* Th 6–9 and *e* Th 6–10

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524	Th 6 — Th 10	50

The same operation was performed step by step on 3 rabbits from the sixth to tenth thoracic vertebrae. The results are seen in Table IV and are illustrated in Fig. 2.

TABLE IV — *Immediate results in 3 rabbits of transection of the costotransverse ligament performed unilaterally step by step in one sequence at different numbers of levels*

Location of operation	Average scoliosis in degree
Th 6	1[illegible]
Th 6 — Th 7	13
Th 6 — Th 8	25
Th 6 — Th 9	3[illegible]
Th 6 — Th 10	40

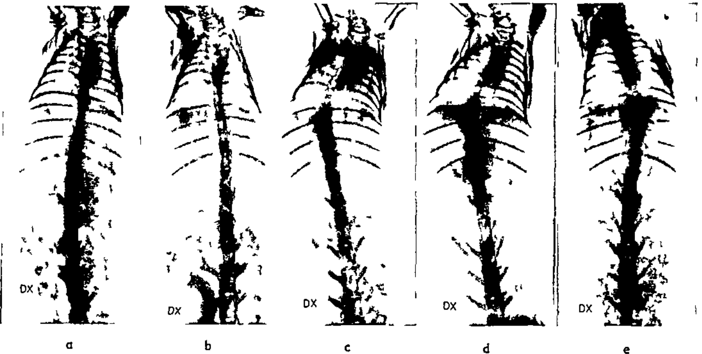


Fig 3 Rabbit Several different procedures were carried out in one sequence at the seventh to eleventh ribs at the age of 80 days Radiographs were taken *immediately after each operative phase* *a No scoliosis is resulting after resection of the sacro spinalis performed* on the right side nor after resection of the deeper back muscles *b c* Transection of the costotransverse ligaments on the right side subsequently performed resulted in scoliosis *d* The position of the spine was not changed after resection of the deep back muscles on the left side *e* By resection of the dorsal ends of the rib performed on the left side immediately afterwards the scoliosis was transferred *to the left side*



a b c d

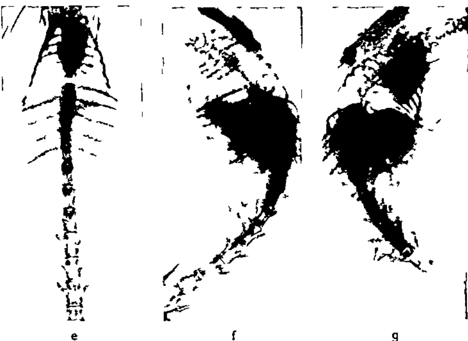


Fig 4 Rabbit Transection of the costotransverse ligaments and the dorsal portions of the intercostal muscles at the sixth to tenth intercostal spaces on the right side at the age of two months *a–d* Alive immediately after operation *a* In resting position *b* By tension in longitudinal direction Straightening of the spine *c* In forcible lateral flexion toward the right side The primary curve is rigid *d* In forcible lateral flexion toward the left side *e–g* Killed immediately afterward *e* In resting position Complete straightening of the scoliosis *f* and *g* In lateral flexion the rigidity of the primary curve has disappeared

thoracic operations resulting in scoliosis except resection of the dorsal ends of ribs and transection of both the costotransverse ligaments and intercostal muscles (Tables XI and XII) As a rule regression occurred during the first six weeks after the development of scoliosis (Fig 5) Regression was a particularly common finding after operations followed by marked cicatrization and after operations which only slightly affected the contact between the ribs and the vertebrae The diagrams in Fig 5 and 6 illustrate some typical courses

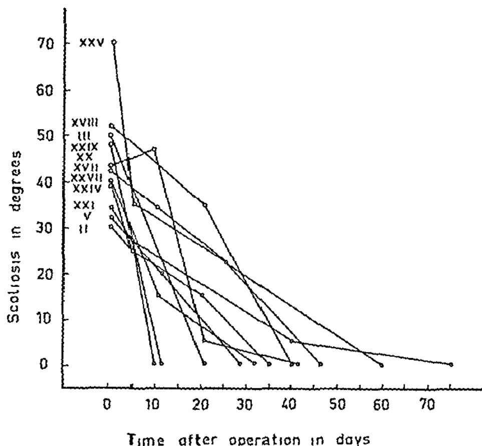


Fig 5 Examples of regressive scoliosis in rabbits provoked by eleven different operations found to produce this condition The Roman numerals indicate the kind of operation (see Table I) As a rule regression occurred within six to eight weeks after operation

C Structural scoliosis

The provocation and course of structural scoliosis

Structural scoliosis resulted either from the operations which had caused initial functional scoliosis or from certain fixative operations Those operations consisting of resection transection transposition or electrocoagulation of various structures which did not lead to functional scoliosis did not result in later structural scoliosis either See Table I page 16

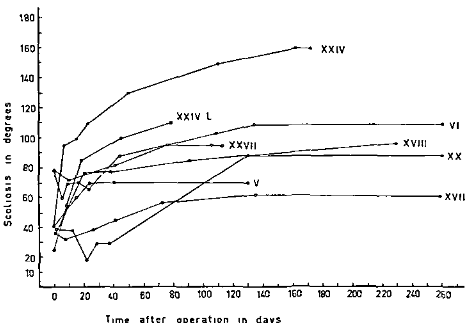


Fig 6 Examples of the course of progressive scoliosis The 8 rabbits were operated upon by different methods found to produce this condition The Roman numeral indicate the kind of operation (see Table I) Progression mainly occurred during the first six to eight weeks after operation

From the standpoint of lateral deviation the functional scoliosis ran different courses In some animals the scoliosis exhibited a steady regression or alternating progression and regression while in a large number of cases a steady progression occurred

Examples of both increase and decrease of the scoliosis were seen throughout the period of growth but in both rabbits and pigs regression as well as progression mainly occurred during the first two months after the development of scoliosis see Fig 5 and 6

The development of structural scoliosis from functional scoliosis in rabbits

After all those operations involving the resection or transection of various structures which led to functional scoliosis a permanent structural scoliosis

TABLE XI — *Structural scoliosis in rabbits resulting from resection or transection of different structures in the spine or its vicinity*

All operations were performed unilaterally at five levels. The position of the spine was radiologically recorded a minimum of two months after operation

Operation	Scoliosis in degrees			No. of rabbits
	Average	Min	Max	
Simple thoracic operations				
Resection of the dorsal ends of the ribs	[illegible]	[illegible]	170	35
Hemilaminectomy	[illegible]	0	180	35
Transection of the ligaments of the head of the rib	55	0	[illegible]	14
Transection of the ligaments attached to the dorsal ends of the ribs	45	0	100	[illegible]
Resection of the ribs laterally of their tubercles	41	0	110	[illegible]
Resection of the heads of the ribs	31	0	[illegible]	[illegible]
Transection of the costotransverse ligament	[illegible]	0	90	[illegible]
Transection of the thoracic wall	21	0	60	8
Transversectomy	17	0	45	5
Transection of the intercostal muscles	16	0	48	3
Transection of the intercostal nerves	16	0	85	13
Provoked epiphysiolysis of the heads or transection of the necks of the ribs	13	0	41	1
Combined thoracic operations				
Transection of the costotransverse ligaments and the intercostal muscles	63	55	[illegible]	3
Transection of the costotransverse ligaments and the intercostal nerves	34	0	90	8
Lumbar operations				
Hemilaminectomy	49	15	110	8
Transection of all muscles and ligaments attached to the transverse processes and the arches	[illegible]	17	35	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	
			Total	[illegible]

developed in some animal The re ults in the rabbits after a minimum of two months are compiled in Tables XI and XII

With regard to degree no definite correlation was di cernible between functional scolio i and the sub equent structural condition (Table XIII) All animal on which the dor al end of ribs had been re ected or both costo-transver e ligaments and intercostal muscle had been cut developed perma nent structural scoliosis but after all other thoracic operation provoking scolio is complete reg e sion occurred in some cases After one and the ame operation too wide variation in the degree of the scolio is were een

Summary of the effect on rabbits of different operations provoking scoliosis

For the sake of comparison Table XIII ha been compiled to illu trate the functional and tructural scolio i induced by different operations in volving the resection or transection of various structures in the spine or its vicinity The table show the average degree of colio is re ulting from the different operations and their relative efficacy The re ults of the operations de cribed in the foregoing may be summarized a follow

Simple thoracic operations

Resection of the dorsal ends of ribs led to the severe t average functional and structural colio i In no case wa complete regre ion of the scoliosi observed but wide variations in degree occurred

Resection of ribs laterally of their tubercles resulted in functional and structural scoliosis which was much slighter than in the foregoing ca e The farther laterally of the tubercle the re ection was performed and the smaller the piece re ected the slighter was the re ulting scolio is Only one out of 21 cases showed complete regre sion

Transection of ribs and the corresponding intercostal nerves and vessels led to slight functional scoliosis Of 8 rabbits 5 developed structural scolio sis up to 60 degree

Resection of the heads of ribs resulted in evere functional scoliosis and much slighter structural scolio i Of 5 ca es one showed complete regression

Provoked epiphysiolysis of the heads or transection of the necks of ribs induced severe functional scolio is which in all cases regres ed In 5 ca e

TABLE XII — *Structural scoliosis in rabbits resulting from resection or transection of different structures in the spine or its vicinity*

The same animals as appear in Table XI. The position of the spine was radiologically recorded a minimum of two months after operation

Operation	No of rabbits						
	Scoliosis in degrees						
	0	1–9	10–19	20–29	30–39	40–49	50–59
Simple thoracic operations							
Resection of the dorsal ends of the rib				[illegible]	1	2	4
Hemilaminectomy	4		3	[illegible]	4	3	3
Transection of the ligaments of the heads of the rib	3			1	2		1
Transection of the ligaments attached to the dorsal ends of the rib	1		1	1	2	2	2
Resection of the ribs laterally of their tubercles	1		4	3	4	2	1
Resection of the heads of the ribs	1			1	1		
Transection of the costotransverse ligaments	[illegible]		2	2		1	1
Transection of the thoracic wall	3	1	1		1	1	
Transversectomy	3					2	
Transection of the intercostal muscles	2					1	
Transection of the intercostal nerves	8		2				2
Provoked epiphysiolysis of the heads or transection of the necks of the rib	[illegible]	1	3	1		[illegible]	
Combined thoracic operations							
Transection of the costotransverse ligaments and the intercostal muscles							1
Transection of the costotransverse ligaments and the intercostal nerves	2		1	1			
Lumbar operations							
Hemilaminectomy			[illegible]		1		1
Transection of all muscles and ligaments attached to the transverse processes and the arches			1	[illegible]	3		
Transversectomy				[illegible]			

No of rabbit											
Scoliosis in degrees											
60–69	70–79	80–89	90–99	100–109	110–119	120–129	130–139	140–149	150–159	160–169	170–179
1	4	5	5		6	[illegible]					1
4	1	3		1	1	[illegible]				1	
1	2	1	1	1		1					
		1	1	1							
1	[illegible]	1	1		1						
[illegible]											
			1								
1											
		1									
1	1										
1			1								
			1		1						

TABLE XII — *Structural scoliosis in rabbits resulting from resection or transection of different structures in the spine or its vicinity*

The same animals as appear in Table XI. The position of the spine was radiologically recorded a minimum of two months after operation

Operation	No of rabbits						
	Scoliosis in degree						
	0	*1—9*	*10—19*	*20—29*	*30—39*	*40—49*	*50—59*
Simple thoracic operations							
Resection of the dorsal ends of the ribs				2	1	2	4
Hemilaminectomy	4		3	2	4	3	3
Transection of the ligaments of the heads of the ribs	3			1	2		1
Transection of the ligaments attached to the dorsal ends of the rib	1		1	1	2	2	2
Resection of the ribs laterally of their tubercles	1		4	3	4	2	1
Resection of the heads of the ribs	1			1	1		
Transection of the costotransverse ligaments	5		2	[illegible]		1	1
Transection of the thoracic wall	3	1	1		1	1	
Transversectomy	3					2	
Transection of the intercostal muscles	2					1	
Transection of the intercostal nerves	8		2				[illegible]
Provoked epiphysiolysis of the heads or transection of the necks of the ribs	5	1	3	1		2	
Combined thoracic operations							
Transection of the costotransverse ligaments and the intercostal muscles							1
Transection of the costotransverse ligaments and the intercostal nerves	[illegible]		1	1		2	
Lumbar operations							
Hemilaminectomy					1		1
Transection of all muscles and ligaments attached to the transverse processes and the arches			1	2	3		
Transversectomy							

No of rabbits													
Scolio[sis] in degree													Total
60–69	70–79	80–89	90–99	100–109	110–119	120–129	130–139	140–149	150–159	160–169	170–179	180	
1	4	5	5		6						1		35
4	1	3		1	1					1		1	35
1	2	1	1	1		1							14
		1	1	1									12
1	2	1	1		1								21
2													5
			1										12
1													8
													5
													3
		1											13
													12
1	1												3
1			1										8
			1		1								8
													6
													2

TABLE XIII — *Comparison of functional and structural scoliosis in rabbits resulting from resection or transection of different structures in the spine or its vicinity*

The same animals appear in Tables II and XI

The numbers 1—12 indicate the order of the operations in regard to efficacy in producing scoliosis

Operation	Funct. scoliosis		Struct. scoliosis	
	Order of efficacy	Average scoliosis in degrees	Order of efficacy	Average scoliosis in degrees
Simple thoracic operations				
Resection of the dorsal end of the rib	1	51	1	86
Resection of the head of the rib	[illegible]	51	6	34
Provoked epiphysiolysis of the head or transection of the neck of the rib	3	51	12	13
Transection of the ligaments of the head of the rib	4	49	3	[illegible]
Transection of the intercostal muscles	5	49	10	[illegible]
Transection of the costotransverse ligament	6	44	[illegible]	[illegible]
Hemilaminectomy	[illegible]	44	2	[illegible]
Transection of the ligaments attached to the dorsal end of the rib	8	38	4	[illegible]
Transection of the intercostal nerve	9	37	11	16
Resection of the ribs laterally of their tubercles	10	35	5	41
Transection of the thoracic wall	11	1	8	21
Transversectomy	1	18	9	17
Combined thoracic operations				
Transection of the costotransverse ligament and the intercostal muscle	1	73	1	63
Transection of the costotransverse ligaments and the intercostal nerve		61	2	34
Lumbar operations				
Transection of the muscles and ligaments attached to the transverse processes and the arches	1	40	2	[illegible]
Transversectomy	[illegible]	3	3	[illegible]
Hemilaminectomy	3	17	1	40

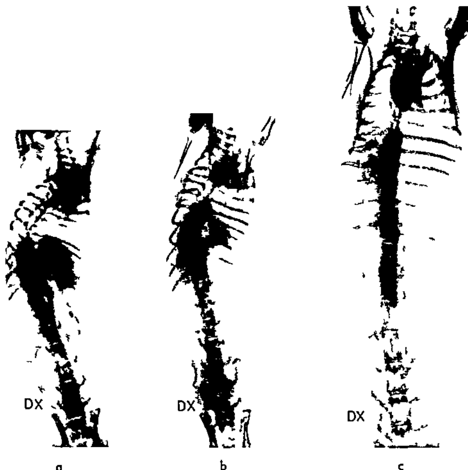


Fig 7 Rabbit Transection of the necks of the sixth to tenth ribs on the right side performed at the age of 0 days *a* Immediately after operation scoliosis of 60 degrees *b* Ten days after operation scoliosis of 45 degrees *c* Forty five days after operation only slight scoliosis Abundant cicatrization in the area of the operation

out of 12 regression was complete After these operations marked cicatrization was often observable See Fig 7

Transection of the ligaments of the heads of ribs led to relatively severe functional and structural scoliosis Complete regression occurred in 3 out of 14 cases There were wide variations in the degree of the scoliosis

TABLE XIII — *Comparison of functional and structural scoliosis in rabbits resulting from resection or transection of different structures in the spine or its vicinity*

The same animals as appear in Tables II and XI

The numbers 1—12 indicate the order of the operations in regard to efficacy in producing scoliosis

Operation	Funct. scoliosis		Struct. scoliosis	
	Order of efficacy	Average scoliosis in degrees	Order of efficacy	Average scoliosis in degrees
Simple thoracic operations				
Resection of the dorsal ends of the ribs	1	51	1	86
Resection of the heads of the ribs	2	51	6	31
Provoked epiphysiolysis of the head or transection of the necks of the ribs	3	51	12	13
Transection of the ligaments of the head of the ribs	4	49	3	55
Transection of the intercostal muscles	5	49	10	16
Transection of the costotransverse ligaments	6	44	7	
Hemilaminectomy	7	41	2	54
Transection of the ligaments attached to the dorsal ends of the ribs	8	38	4	43
Transection of the intercostal nerve	9	37	11	16
Resection of the ribs laterally of their tubercles	10	35	5	41
Transection of the thoracic wall	11	21	8	21
Transversectomy	12	18	9	17
Combined thoracic operations				
Transection of the costotransverse ligaments and the intercostal muscle	1	73	1	67
Transection of the costotransverse ligaments and the intercostal nerve	2	61	2	31
Lumbar operations				
Transection of the muscles and ligaments attached to the transverse processes and the arches	1	40	2	24
Transversectomy		3	3	7
Hemilaminectomy	3	17	1	47

Transection of intercostal nerves resulted in moderate functional scoliosis but of 13 animals only 5 developed structural scoliosis (up to 85 degrees).
Transverseclomy in the thoracic region led to only slight functional and structural scoliosis.

Combined thoracic operations

Transection of both costotransverse ligaments and intercostal muscles resulted in severe functional and structural scoliosis in all rabbits. It should be noted that when carried out alone the different procedures led to structural scoliosis which was on the average slight.
Transection of costotransverse ligaments and intercostal nerves produced severe functional scoliosis. Of 8 rabbits 2 showed complete regression while the remainder developed structural scoliosis up to 90 degrees.
After all the above mentioned thoracic operations the primary curve was convex to the side of the operation in both functional and structural scoliosis.

Lumbar operations

Transection of the muscles and ligaments between the transverse processes and between these and the arches resulted in relatively severe functional scoliosis which was convex towards the operated side. The resultant structural scoliosis was slight. In one case it was directed towards the side of the operation in 5 cases towards the intact side. Furthermore 2 rabbits showed severe apparent kyphosis.
Transverseclomy in the lumbar region led to only slight functional scoliosis which was convex towards the side of the operation. The subsequent structural scoliosis was associated with slight lordosis. In one of 2 animals the scoliosis was directed towards the operated side while in the other it was convex to the intact side.
Hemilaminectomy provoked slight functional scoliosis directed towards the side of the operation. All animals developed permanent structural scoliosis. The convexity was in 6 cases directed towards the operated side, in 2 cases towards the intact side. In addition 4 rabbits developed kyphosis up to 90 degrees (See Fig. 9).
After all the above mentioned lumbar operations the primary curve of the functional scoliosis was invariably convex to the side of the operation. While the condition developed into the structural form the scoliosis was in some cases gradually transferred to the other side.

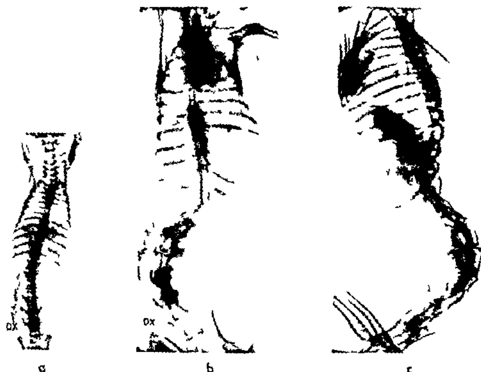


Fig. 9. Rabbit. Hemilaminectomy of the first to fifth lumbar vertebrae on the right side performed at the age of 30 days. a: Immediately after operation; b and c: Fourteen months after operation, showing scoliosis of 90 degrees and kyphosis of 100 degrees.

The development of structural scoliosis from functional scoliosis in pigs

Just as in the rabbits, structural scoliosis resulted in the pigs after all those operations involving the transection or resection of various structures in the spine or its vicinity which had led to functional scoliosis. After the different operations, structural scoliosis was mostly somewhat slighter in the pigs than in the rabbits. The results in the pigs, a minimum of two months after operation, are compiled in Table [illegible].

Resection of the dorsal ends of ribs including both costal joint surfaces in [illegible] pigs resulted in structural scoliosis of an average of 34 degrees, the minimum being 18 degrees and the maximum 77 degrees.

Hemilaminectomy and transversectomy were performed on one pig, which developed structural scoliosis of 30 degrees. *Incomplete hemilaminectomy*

TABLE XIV. *Structural scoliosis in pigs resulting from resection or transection of different structures in the spine or its vicinity*

All operations were performed unilaterally at five levels. The position of the spine was radiologically recorded a minimum of two months after operation

Operation	No. of pigs									
	Scoliosis in degrees									
	0	1–9	10–19	20–29	30–39	40–49	50–59	60–69	70–79	Total
Transection of the intercostal muscles and the costotransverse ligament						1				1
Transection of the intercostal muscle					2	1				3
Transection of the costotransverse ligaments			1	1	1	1				4
Resection of the dorsal ends of the ribs			2	8	6	1	1		1	19
Resection of the heads of the ribs					1					1
Hemilaminectomy and transversectomy					1					1
Transection of the ligaments attached to the lateral ends of the ribs			1							1

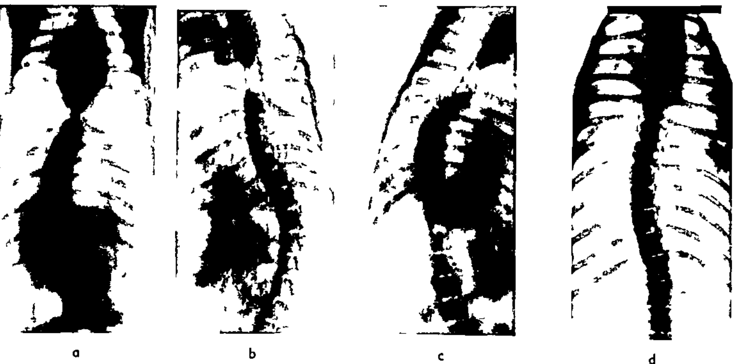


Fig. 10. Dog. Transection of the costotransverse ligaments at the seventh to eleventh intercostal spaces on the right side performed at the age of two months. *a–c* Radiographs taken one month after operation. *a* Resting position. *b* Lateral flexion towards the side of the operation. Primary curve is rigid. *c* Lateral flexion towards the intact side. Secondary curves are rigid. *d* Animal killed and skeletonized two months after operation. Scoliosis of 30 degrees. Note rotation of vertebrae and drooping of ribs on the operated side.

(not including the articular processes) was done on one pig without any scoliosis resulting

Resection of the heads of ribs was performed on one pig Structural scoliosis of 30 degrees resulted

Transection of all ligaments attaching the dorsal ends of ribs to the spine was carried out on one pig which developed structural scoliosis of 15 degrees

Transection of intercostal muscles in 3 pigs resulted in structural scoliosis averaging 37 degrees the minimum being 35 and the maximum 40 degree

Transection of costotransverse ligaments led in 4 cases to structural scoliosis of an average of 31 degrees the minimum being 17 and the maximum 46 degrees See Fig 10

Transection of both intercostal muscles and costotransverse ligaments was carried out on one pig which developed structural scoliosis of 10 degrees

The effect of fixation of different skeletal parts to each other in rabbits and pigs

On growing rabbits and pigs the following fixative operations were done with nylon thread

1 *Fixation of five to six transverse processes* in the thoracic region to each other was performed on 28 rabbits 14 of which developed scoliosis up to 90 degrees

2 *Fixation of three to seven ribs* to each other was performed on 20 rabbit In 7 cases scoliosis up to 90 degrees developed The result was dependent on the site of fixation In those animal in which scoliosis developed the nylon thread was tied around the ribs near their tubercles On 2 rabbits *fixation of five ribs was done on one side in association with transection of the costotransverse ligaments at the same levels on the contralateral side* Both animals developed structural scoliosis of 50 degrees and in addition apparent kyphosis

3 *Fixation of spinous processes to ribs* was carried out in various ways on 9 rabbits and 8 pig Marked scoliosis resulted only when the spinous processes were fixed to ribs situated several levels cranially or caudally of them and the thread was tied around the ribs near their tubercles Figs 11 and 12 show the scolio i thus produced in rabbits and pigs

Immediately after fixation no appreciable changes in the position of the spine were observable The structural scoliosis provoked by these operations developed gradually and as a rule steadily progre ed throughout the whole

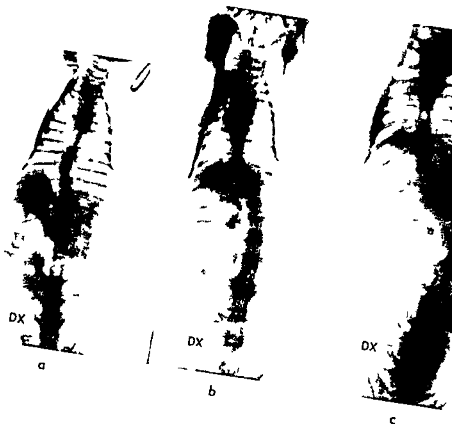


Fig 11 Rabbit. Fixation with nylon thread of the spinous processes of the ninth to eleventh thoracic vertebrae and the tenth to twelfth rib to the spinous process of the second to fourth lumbar vertebrae on the right side performed at ... a half month. The ... of ... eventually ... thread to ... lumbar spinous process was ... Immediately after ... after ... operation ... and ... the ...



Fig 1 Fig Fixation with nylon thread of the spinous processes of the seventh to ninth thoracic vertebrae to the ninth to thirteenth ribs on the right side performed at the age of two months *a* Two weeks after operation *b* Two and a half months after operation *c* Specimen half a year after operation

period of longitudinal growth This form of scoliosis was always convex to the intact side and it was often associated with lordosis or kyphosis of the region involved in fixation

The general features of structural scoliosis

A primary curve and one or more secondary curves always occurred in structural scoliosis The convexity of the primary curve was directed towards the side of the operation after all procedures except the fixations and *some lumbar operations*

Rigidity of both the primary and the secondary curves was a constant phenomenon and usually the rigidity steadily increased (Figs 10 15 and 16) As a rule the scoliosis was somewhat straightened by tension of the spine in the longitudinal direction (Fig 15) immediately *post mortem* (Fig 15 and 16) and in deep anaesthesia but it never became completely straight as was the case in functional scoliosis immediately after operation



a



b



c



d

Fig. 11. Rabbit. Fixation with nylon thread of the spinous processes of the ninth to eleventh thoracic vertebrae and the tenth to twelfth ribs to the spinous processes of the second to fourth lumbar vertebrae on the right side performed at the age of one and a half months. The site of fixation of the most caudally situated thread to the [illegible] lumbar spinous process was marked with thread *a*. Immediately after operation *b*. One month after operation *c* and *d*. Seven months after operation [illegible] of 70 [illegible]

Drooping of the ribs on the convex side of the primary curve was a frequent finding

Rib humps usually a dorsal hump on the convex side and a ventral hump on the concave side occurred in thoracic scoliosis

All the above mentioned phenomena and many other adaptational changes of the spine and its surrounding structures were observable in structural scoliosis in both rabbits and pigs Similar changes occur in man (KLEINBERG LINDEMANN LORENZ LOVETT V NICOLADONI SCHULTHESS)

Initial adaptive structural changes of the spine and its surrounding parts

In order to study the initial changes of various soft parts occurring in experimental scoliosis 10 growing rabbits were investigated more closely for a period of time after scoliosis had been provoked

Fig 15 illustrates an experiment in which scoliosis was provoked in a rabbit by transection of the ligaments of the heads of five ribs The animal was radiologically studied one day after operation both alive and post mortem after dissection step by step Fig 16 illustrates an experiment in which a rabbit was operated upon and investigated in the same way five days after operation

The results of these studies showed the following

Immediately after operation scoliosis developed which began to progress

The scoliosis was somewhat straightened by tension in the longitudinal direction of the spine twenty four hours after operation (Fig 15 b)

At the primary curve the lateral flexibility of the spine was abnormally increased toward the intact (concave) side and decreased towards the operated (convex) side Both the primary and the secondary curves were more or less rigid (Fig 15 d and e and 16 b and c)

Post mortem only partial straightening of the spine occurred in both the sagittal and the frontal plane not complete straightening as in functional scoliosis (Fig 15 f and 16 d) and the changes in lateral flexibility were less striking (Fig 15 g and h and 16 e and f)

When the thoracic wall and the back muscles had been removed from the specimen the scoliosis showed a further decrease (Fig 15 i and 16 g) but the curves were still definitely rigid (Fig 15 j and k and 16 h and i)

After removal of the surrounding structures the curves of both the bodies and arches of the vertebral column were still found to be somewhat rigid (Fig 15 l—o and 16 j—m)

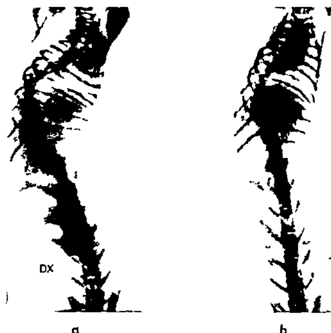


Fig. 15. Rabbit. Transection of the ligaments attached to the heads of the sixth to tenth ribs was performed on the right side at the age of 75 days. Radiographs taken immediately after operation (*a*) and one day after operation (*b*—*p*).

a. In resting position immediately after operation. *b*. One day after operation in tension in the longitudinal direction. Slight straightening of the scoliosis (cf. Fig. 15 e).

Alive in resting position (*c*), in flexion toward the right side (*d*) and toward the left side (*e*). The curves are rigid.

Specimen kept freely (*f*), in lateral flexion toward the right side (*g*) and toward the left side (*h*). The curves are less rigid than in vivo.

The spine kept freely (*i*), in lateral flexion toward the right side (*j*) and toward the left side (*k*). The curves are still moderately rigid.

The bodies and arches of the vertebral column kept freely (*l* and *m*), in lateral flexion toward the right side (*n*) and toward the left side (*o*). The primary curve is moderately rigid (*p*). The thoracic wall spread out. The half on the convex side is markedly broader than the half on the concave side.



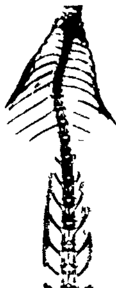
c



d



e



f

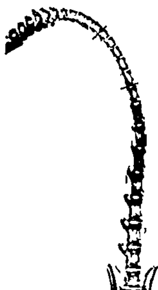


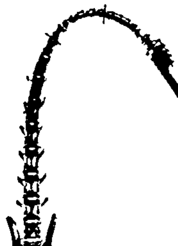
g



h

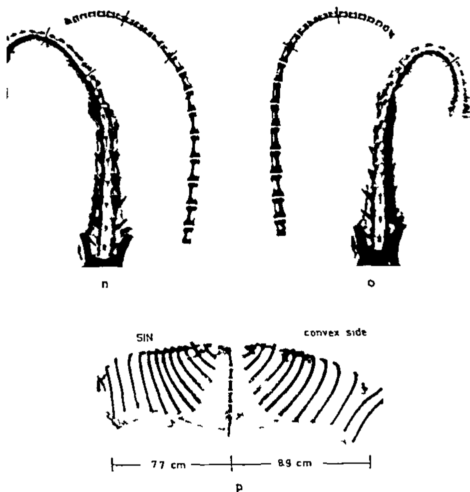

i


j


k


l


m



When di ected out the thoracic wall was found to be definitely asym metric the concave ide being markedly narrower than the convex side (Fig 15 p and 16 n)

As early as one day after the development of functional scoliosis structural changes had developed simultaneously in the spine and its surrounding struc tures After five days the changes had progressed The e phenomena were verified in all the above mentioned experiments


i


j

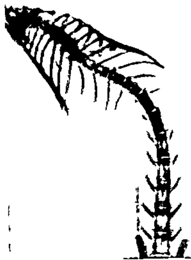

k


l


m



d



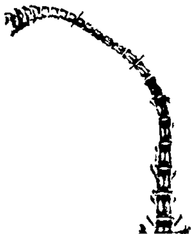
e



f



g



h



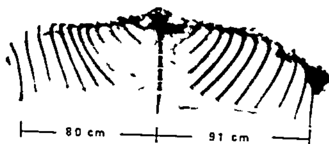
i


j


k


l
SIN


convex side
m


80 cm
91 cm

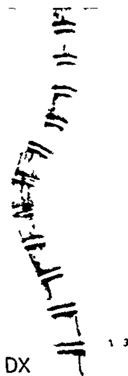
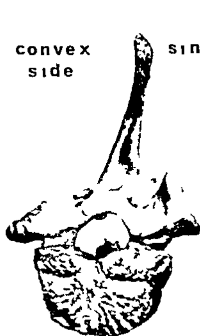
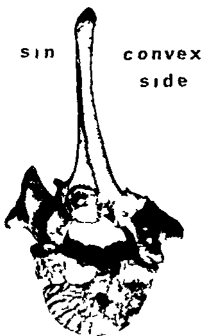


Fig 17 Pig Bodies of a coliotic pine of ~~ degrees provoked by rib resection The animal was killed and di ected half a year after operation Note the wedge hape of *the bodie at the apex of the curve*

Fig 18 1 a The vertebra at the apex of a coli i of 39 degree provoked by rib resection The animal wa killed half a year after operation *a* Cranial view with out epiphy i *b* Caudal vi w without epipl y i Note th di tortion and a ym metry of all parts of the vertebra





The macroscopic changes of the vertebrae

Eight scoliotic pig spines were dissected in order to enable closer study of the vertebrae Almost all vertebrae exhibited changes the greatest changes being found in the vertebrae situated at the apices of the curves the slightest in those outside the curves (Figs 17 and 20)

In the most deformed vertebrae the following changes were observed (Fig 18)

The vertebral body was wedge shaped being much higher on the convex side of the curve The most pronounced changes were seen at the cranial epiphysis on the concave side In the transverse projection the vertebral body was somewhat egg shaped with the larger pole towards the concave

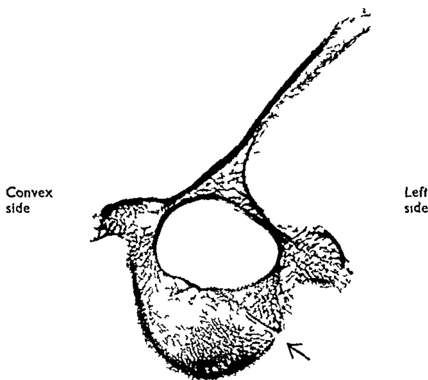


Fig 19 Pig Transverse section of the vertebra at the apex of a scoliosis of 40 degrees provoked by rib resection on the right side at the age of seven weeks The animal was killed at the age of seven months The neurocentral junction is fused on the convex side of the curve and open on the concave side

side On this side the vertebral body and the neurocentral junction were much broader than on the convex side In some animals the neurocentral junctions of certain vertebrae were fused on the convex side while they were still open on the concave side (Fig 19)

The vertebral foramen was mo tly oval and displaced towards the concave side of the curve in relation to the vertebral body

The arch was much lower and thicker on the concave side and both halves of the arch were oblique and di placed towards the concave side

The articular processes were usually broader and thicker on the concave side

The transverse process was as a rule descendent short and thick on the convex side of the curve and ascendent long and narrow on the concave side

The base of the spinous process was horter and thicker on the concave ide Its basal parts were di placed towards the concave side its dorsal parts toward the convex side

In experimental scoliosis all parts of the vertebrae thus showed deformation The changes were the same as are typical of human idiopathic scoliosis according to KLEINBERG LORENZ *and* LOVETT

Studies on the growth changes of the vertebrae

In order to study the growth change of the vertebrae in colio i different parts of scoliotic vertebrae were mea ured Furthermore in spines in which structural scoliosis was to be provoked certain vertebrae were marked with vitallium crews

1 *Studies on the longitudinal growth of the vertebrae*

The vertebrae of 2 coliotic pig spine were di sected and the height of the vertebral bodies and the pedicle of the arches were measured with calipers on both the convex and the concave side of the curve In addition the corre ponding parts of normal vertebrae of pigs of the same age were mea ured The re ults of these measurements are shown in Fig 20

The vertebrae at the apex of the primary curve showed the greatest deformation tho e outside the curves the lighte t The vertebral bodies were higher than normal on the convex side lower than normal on the concave ide The arche were much lower than normal on the concave side while on the convex ide they were sometime equally high sometimes

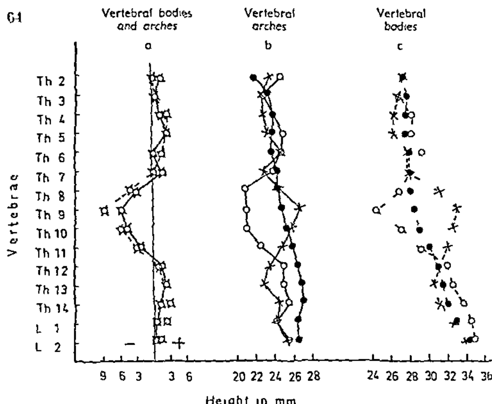


Fig 40 Diagrammatic representation of the longitudinal growth changes of the vertebrae in scoliosis The height of the pedicles of the vertebral arches and of the vertebral bodies was measured at corresponding points on the right and left side in a scoliotic and a normal pig of the same age Scoliosis was induced by resection of the dorsal ends of the seventh to eleventh ribs on the right side On dissection four months after operation there was scoliosis of 40 degrees with the apex of the primary curve at the ninth thoracic vertebra

a The differences in height between the right and left sides of the bodies and of the pedicles of the arches of the scoliotic pig Note that the differences are much greater at the primary curve than at the secondary curve

¤ - ¤ - - ¤ Differences in height of the vertebral bodies on the right and left sides

¤——¤——¤ Differences in height of the pedicles of the arches on the right and left sides

— The right side higher

+ The left side higher

b Height of the right and left sides of the pedicles of the arches of the scoliotic and the normal pig

×——×——× Height of the pedicles of the arches of the scoliotic pig on the right side

○——○——○ Height of the pedicles of the arches of the scoliotic pig on the left side

●——●——● Height of the pedicles of the arches of the normal pig (the same on both sides)

c Height of the right and left sides of the vertebral bodies of the scoliotic and the normal pig

×- - - × - - × Height of the vertebral bodies of the scoliotic pig on the right side

○- - - ○- - - ○ Height of the vertebral bodies of the scoliotic pig on the left side

●- - ●- - ● Height of the vertebral bodies of the normal pig (the same on both sides)

The arches and bodies of the scoliotic spine are higher than normal on the convex side and lower than normal on the concave side at the apex of the primary curve

somewhat higher and sometimes somewhat lower than normal depending on the deviation of the spine in the sagittal plane

These studies show that the longitudinal growth of the vertebral body and often of the arch too had been increased on the convex side while retardation of the longitudinal growth of both the vertebral body and the arch had occurred on the concave side of the curve

2 *Studies on the lateral growth of the vertebrae*

In cooperation with A LANGENSKIÖLD some preliminary studies on the incorporation of alizarin in the vertebrae of rabbits during progression of experimental scoliosis were carried out These studies indicated that the madder dye was especially accumulated on the concave side of the vertebral bodies

In 5 growing pigs certain vertebrae were marked with vitallium screws and simultaneously an operation producing scoliosis was performed in such a way that the marked vertebra came to be situated in the middle of the primary curve

Fig 21 illustrates one of these experiments In a seven week-old pig two screws were symmetrically applied one to each side of the basal part of the spinous process of a vertebra and at the same time rib resection was unilaterally performed The pig was killed half a year later showing scoliosis of 36 degrees The screws were still situated at the base of the spinous process but on the convex side of the curve the screw lay much nearer the lateral surface than the screw on the concave side

Furthermore screws were symmetrically applied to the body of a vertebra in a two month old pig one to each side immediately ventrally of the neurocentral junction and at the same time transection of intercostal muscles was unilaterally performed Scoliosis of 35 degrees had developed when the animal was killed half a year later On the concave side the screw was found to be situated much deeper in the vertebral body i e farther from both the lateral and the ventral surface of the latter than the screw on the convex side (Fig 22)

These experiments show that increased lateral growth (apposition) had occurred in both the vertebral body and the arch on the concave side of the curve while the apposition was much slighter on the convex side Thus the scoliotic vertebrae had grown in the lateral direction much more towards the concave than towards the convex side The regular occurrence of these phenomena in experimental scoliosis has later been confirmed by KARAHARJU in experiments with tetracycline



Fig. 71. Fig. At the age of seven weeks screws were symmetrically applied to both sides of the basal part of the spinous process of the ninth thoracic vertebra as shown in *a*. Simultaneously the seventh to eleventh ribs were resected on the right side. Scoliosis *of 36 degrees developed with the ninth thoracic vertebra situated at the apex. The animal* was killed half a year after operation. Note that the screws are situated further toward the convex side than toward the concave side of the curve *b*.



Fig. [illegible] At the age of two months screws were applied as symmetrically as possible one to each side of the body of the ninth thoracic vertebra as in *a*. Simultaneously transection of the intercostal muscles of the seventh to eleventh intercostal spaces was performed on the right side. Scoliosis of 35 degrees developed with the ninth thoracic vertebra situated at the apex. The animal was killed half a year after operation. The screw on the concave side [illegible] much deeper in the vertebral body than the screw on *the convex side b.*

Histological findings

Thirty three scoliotic rabbit spines were histologically examined at various points of time after the operation by which scoliosis had been provoked (Fig 23—28)

Summary of the histological studies

The *intervertebral discs* exhibited definite changes as early as one day after scoliosis had been provoked The nuclei pulposi were displaced towards the convex side the fibres of the annuli fibrosi were extended on the convex side and compressed on the concave side The changes of the discs were seen at all stages of scoliosis in the animal investigated

The epiphyseal bony nuclei of the vertebral bodies changed gradually The greatest changes were observable in the cranial bony nuclei which steadily atrophied on the concave side while the corresponding parts of the caudal bony nuclei as a rule became hypertrophied On the convex side the bony nuclei were of about equal thickness

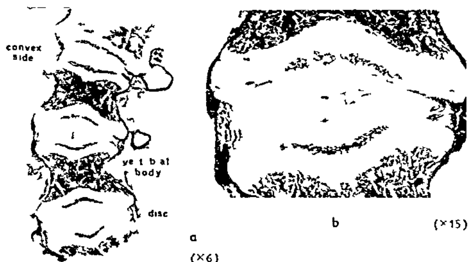


Fig 23 Rabbit Scoliosis was provoked by rib resection at the age of ten days and the animal was killed one *day after operation* *a* Section of vertebrae from apex of the primary curve *b* Magnification of the medial disc in *a* The nucleus pulposus is displaced toward the convex side of the curve The annulus fibrosus is extended on the convex side and compressed on the concave side Somewhat increased sclerosis is seen on the concave side of the body

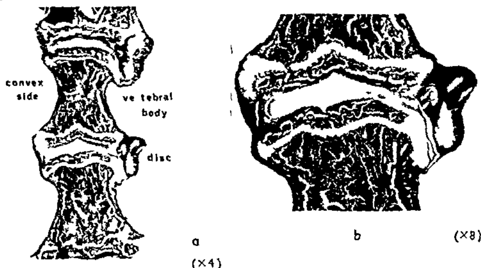


Fig 4 Rabbit Scolio is wa provoked by tran ection of co totran ver e ligaments at the age of 40 days and the animal was killed *10 days after operation* *a* Section of vertebrae from the primary curve *b* Magnification of the medial di c in *a* Di placement of the nucleu pulpo u toward the convex ide and increased sclero is of the bodie on the concave side The annulu fibro u is extended on the convex side and compre sed on the concave ide

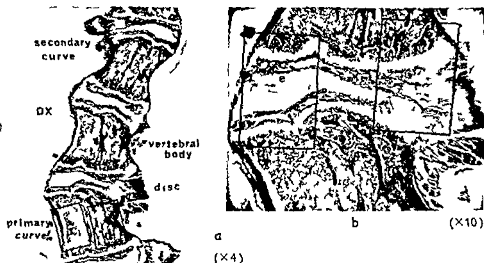


Fig 5 Rabbit Scolio i was provoke l by rib re ection at the a e of eight day The animal w s killed *in m nths after operation* *a* Section of vertebrae from the cranial econdary curve and the primary curve *b* Magnification of a disc of the primary curve in *a* *c* and *d* Magnifications of the areas marked in *a* *e*–*f* Magnifications of the area marked in *b* *g*–*j* Magnifications of the area marked in *e* and *f* The changes in the primary and the econ lary curves are of the same type The nucleus pulpo u is di placed toward the convex id Increa d clerosis is seen on the concave ide The annulu fibro us i extended on th on x ide and compre ed on the concave side Narrowing of the cra nial epiphyseal n i f u i en on the concave side The cartilage column are di arranged on the concave i l i l r ular on the convex ide



c (×30)



d (×30)



e (×30)



f (×30)



g (×185)



h (×185)



i (×185)



j (×185)

The endochondral growth zones of the vertebral bodies underwent a gradual steady change. On the concave side the cranial growth zones in particular were reduced and their cartilage columns were uneven and irregular. On the convex side the cartilage columns of the growth zones were much higher and showed a more regular arrangement than on the concave side.

In the *diaphyses of the vertebral bodies* gradually increasing sclerosis on the concave side and *porosis on the convex side were observable* as early as one day after scoliosis had been induced. The difference in height between the concave and convex sides steadily increased. In severe scoliosis inter body fusion gradually developed in some cases. As a rule the changes of the vertebral bodies were most conspicuous at the cranial epiphyses on the concave side.

The *neurocentral junctions* were narrower and fused much earlier on the convex than on the concave side.

The *vertebral arches* exhibited changes resembling those seen in the vertebral bodies, inasmuch as they were lower and more sclerotic on the concave side of the curve.

All these changes of the vertebral bodies and arches were observable in both the primary and secondary curves in the animals investigated.

The histological changes constitute evidence in favour of the view that the vertebrae had been exposed to increased pressure on the concave side and decreased pressure or increased tension on the convex side of the curves with increased lateral apposition on the concave side and other adaptional changes resulting (see page 81).

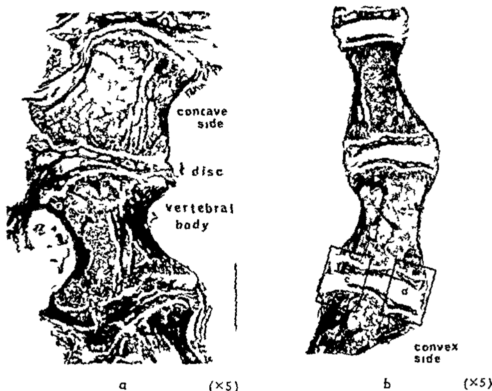


Fig. 6. Rabbit. Scoliosis was provoked by rib resection at the age of six days. The animal was killed *three months after operation*. *a* Section of vertebrae from the primary curve. *b* Vertebrae from the cranial secondary curve. *c* and *d* Magnifications of the areas marked in *b*. *e*–*h* Magnifications of the areas marked in *c* and *d*. The changes in the secondary curve are the same as seen in the primary curve (cf. Fig. [illegible])



c (×25)



d (×25)



e (×110)



f (×110)



g (×110)



h (×110)

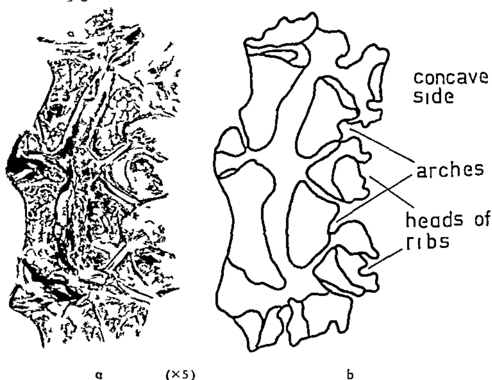


Fig. 7. Rabbit. Scoliosis was provoked by rib resection at the age of six days. The animal was killed *four months after operation*. Section of *arches* from the primary curve. The arches are markedly lower and more sclerotic on the concave side than on the convex side.

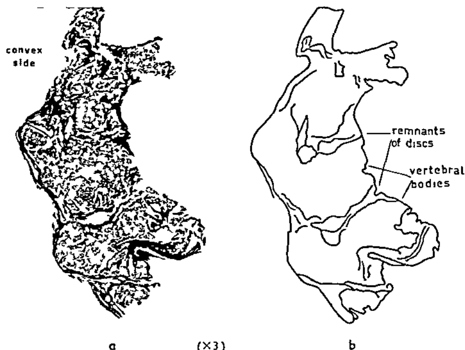


Fig. 8. Rabbit. Scoliosis was provoked by rib resection at the age of nine days. The animal was killed *one year after operation*. Section of the vertebrae from apex of the primary curve. The borderlines between the vertebrae are uneven and in some sites interbody fusion has taken place. The nucleus pulposus is seen on the convex side. Sclerosis is more marked on the concave side than on the convex side.

V DISCUSSION AND CONCLUSIONS

Many investigations have been performed in order to clarify the aetiology and pathogenesis of idiopathic scoliosis, but according to CAREY "most of the evidence presented has consisted of end results of pathologic processes, the courses and starting point of which have been obscure or obliterated in the majority of patients with scoliosis."

Hence there seemed to be reason for undertaking experimental studies on scoliosis in animals, although the static and dynamic conditions of the spine are different in man and quadrupeds. It is known, however, that scoliosis may develop in man during continuous recumbency. This seems to indicate that the erect position of the spine cannot always play an essential part in the development of scoliosis. Thus it appears that not only static but also dynamic factors cause this condition. The numerous reports on scoliosis in quadrupeds (BAYER, CHLUMSKY, ECKHARDT, HARTEL, LINDEMANN, OTTENDORFF, SCHMIDT, SCHULTHESS) seem to constitute further evidence in the same direction.

The development of functional scoliosis. In the experiments described many operations *immediately led to functional scoliosis, which always disappeared* if the animal was killed or subjected to deep anaesthesia within a few hours after operation. This shows that the functional scoliosis was sustained by active muscular forces.

Normally the spine is in a state of dynamic equilibrium. It is almost continuously exposed to the action of dynamic forces (MICHELE, STEINDLER) and consequently the spine and its surrounding structures continuously act upon each other. The dynamic forces are often much stronger than the static ones (CAREY, STEINDLER).

In all operations resulting in initial scoliosis the dynamic equilibrium must have been disturbed in some way or other by the transection or resection of various structures. Owing to the nature of the operation, a weak

ening of active forces must have taken place on the side of the operation while the corresponding forces were still effective on the intact side. Consequently it appears that a unilateral reduction of muscular forces which stabilize the spine in the frontal plane may lead to scoliosis towards the side of the operation unless there are sufficient compensatory force to prevent this outcome.

Of the operations leading to initial scoliosis there were only a few, however, by which dynamic forces (muscles) were directly affected. To facilitate understanding of the results of the different operations the spine may be regarded as an elastic mast of a ship with ribs for yards and muscles and ligaments for stays (BENNINGHOFF, LOB).

The operations which provoked scoliosis either affected active muscular forces directly (resection, transection or denervation of muscles) or were structures operated upon which transfer the action of muscles to the spine (ribs, transverse processes, laminae, ligaments, other muscles).

None of the thoracic operations involving only the deep back muscles led to scoliosis. *It was a common feature in most of the thoracic operations resulting in initial scoliosis that the dorsal ends of ribs or ligaments attaching the ribs to the spine were in some way or other attacked.*

The rib is attached to the spine by several ligaments in such a way that movement of the dorsal end of the rib is markedly limited in both the cranial and the caudal direction. Hence the dorsal end of the rib constitutes a lever for the forces acting on the spine via the rib in the frontal plane, for instance. By various operations ribs (levers) were attacked at or near their main points of support, i.e. at the articulation between the head of the rib and the adjacent vertebral bodies or at the costotransverse joint. This affected the attachment of the rib to the spine and altered its position. Consequently some of the forces acting via the ribs were reduced while the corresponding forces on the intact side were still effective. These operations frequently resulted in scoliosis towards the side of the operation.

One of the few thoracic operations resulting in scoliosis by which the dorsal end of ribs or adjacent parts were not directly affected was the transection of intercostal muscles which usually provoked severe initial scoliosis. The muscles involved act upon the spine via the dorsal ends of the ribs. The different operations on intercostal muscles show that the external and dorsal parts of the muscles in particular have a considerable stabilizing effect on the spine in the frontal plane. Denervation of intercostal muscles (transection of intercostal nerves) invariably led to scoliosis, the average degree of which was lighter, however, than in the scoliosis resulting from

transection of the same muscles. This may, perhaps, be accounted for by the fact that transection of intercostal nerves only led to a weakening of active muscular forces, while both active and passive forces were reduced by the transection of intercostal muscles.

Of the hemilaminectomies performed, only those led to marked scoliosis which were sufficiently radical, i.e. included the portion of the arch situated between the base of the spinous process and the transverse process. By these operations the function of the posterior costotransverse ligament was suspended. Since transection of the anterior and posterior costotransverse ligaments usually resulted in rather severe initial scoliosis, it may be assumed that when the condition developed after hemilaminectomy, one cause must have been the imbalance of the active forces influencing the spine which was due to the loss of function of the posterior costotransverse ligament.

Only a few operations were performed on the lumbar spine. The results seem to indicate that the muscles attached to the transverse processes in the lumbar region of the spine have a marked effect on the position of the latter. Initial scoliosis was mostly milder in degree in the lumbar spine than in the thoracic spine, probably owing to the differences in anatomical conditions. The transverse processes are much more strongly developed and have a different direction in the lumbar spine than in the thoracic spine. In the lumbar region they correspond to some extent to the levers constituted by the ribs in the thoracic spine.

The course of the experimental scoliosis varied even after the same kind of operation.

Comparative studies revealed no definite correlation with regard to degree between functional scoliosis and subsequent structural scoliosis.

It may be stated that the differences in course may be accounted for by compensatory phenomena due to reflexes, by regeneration or healing of the affected tissues and by cicatrization. How the compensatory phenomena due to reflexes arise is not clear. Intense regeneration of affected tissues was observed in the youngest animals in particular, and sometimes resulted in almost complete restoration of the anatomical conditions. Postoperative cicatrization was often abundant, particularly after operations by which periosteal tissue had been injured. *In many cases the scar tissue completely compensated for weakened or removed structures, and occasionally it even caused transition of the scoliosis to the other side.* It is known that in man too scars may affect the position of the spine and cause scoliosis (KLEINBERG, LANGENSKIÖLD & MICHELSSON 1962, LINDEMANN).

Even if no absolutely certain conclusions can be drawn it appears that regression of the scoliosis mainly occurred after such operations provoking this condition where rapid regeneration or healing of the affected tissues was possible or where abundant cicatrization occurred and the scars in conjunction with compensatory forces due to reflexes had anatomical possibilities for acting on the spine either directly or indirectly via other structures

On the other hand severe progressive structural scoliosis developed after those operations inducing this condition where regeneration or healing of the cut or removed structures was inconsiderable or did not occur where cicatrization was slight or the scars and the compensatory forces had fewer anatomical possibilities of influencing the position of the spine

Experimental scoliosis showed the same general features in the main as are typical of human idiopathic scoliosis

Lateral flexibility In man a change in the lateral flexibility of the spine often constitutes the first sign of incipient scoliosis In our laboratory animal the lateral flexibility of the spine exhibited changes immediately after the operations by which scoliosis had been induced (Fig 4 page 34) The apparent rigidity of the primary curve observable immediately after operation may at first sight seem to be a puzzling finding since it was obviously not due to adaptional changes of soft part or bones The fact that the change in lateral flexibility disappeared almost completely when the animal was killed within a few hours after the development of initial scoliosis seems to indicate that this change was mainly dependent on active force That identical change in lateral flexibility were caused by different operation i e by operations on either muscles nerves or bones is more easily understood if the spine is regarded as an elastic mast stayed by forces which in part act via the ribs These forces are derived in part from active structure (muscle in part from passive structures (ligaments or muscles) The operative procedure influenced the complicated staying system of the spine in which the different structure are dependent on each other Equal flexion to both sides were again achieved only when the corresponding structures on the intact side were subjected to the same kind of treatment as had initially produced scoliosis When adaptive structural changes in the spine and its vicinity had developed the changes in lateral flexibility were in part due to contraction of soft parts and structural change of vertebrae but probably those (dynamic factors too which were responsible for the altered lateral flexibility in functional scoliosis still played a part

Rotation of vertebrae No rotation of vertebrae was observable in functional scoliosis This change developed only gradually The rotation of the bodies of the vertebrae was always directed towards the convex side of the curve and it increased in some cases throughout the period of growth but no definite correlation was discernible between the degree of rotation and lateral deviation Because of the complexity of the system of forces influencing the spine, the causes of rotation cannot easily be under tood Owing to the structure of the vertebrae and their fixation on each other and to the ribs by soft parts their normal rotational movements are relatively slight It may be assumed that in scoliosis rotation, too is to a considerable extent due to the forces acting on the spine via the ribs Operations which produce scoliosis probably cause imbalance also of the force acting on the vertebrae *in the transverse plane and thus is likely to result in* rotational movements between the different vertebrae When adaptive changes of the soft parts have developed rotation is likely to increase and this may lead to subluxation between the vertebrae Furthermore rotation may be influenced by the adaptational structural changes of the vertebrae which gradually develop Simultaneously with rotation of the vertebrae adaptive changes of the ribs *e g* humps obviously arise

The effect of different fixative operations Fixation caused imbalance of the forces acting on the spine by the introduction of new forces while by the other operations resulting in scoliosis forces were suspended The fixative operations were performed on the basis of the experience gained from the other procedures The new forces were thus applied to the dorsal ends of certain ribs and vertebrae The results (page 49) show that *fixation led to scoliosis only in those cases where the anatomical conditions were suitable for such an operation where the growth potency of the region of the spine lying between the fixed skeletal parts was high and where the fixation of ribs was done near their tubercles* The growth potency of the region involved by fixation was of e sential significance The effect of this kind of operation depends on the fact that the growth of the vertebrae increases the tension in the thread used for fixation and thereby also the compression to which the vertebrae on the side of the operation are exposed This accounts for the results obtained *The younger the animal and the greater the number of vertebrae involved by the fixative operation the severer was the scoliosis resulting* That fixation of ribs done far laterally of their tubercles as a rule did not lead to scoliosis while the same procedure when performed at the tubercles usually resulted in progressive scoliosis may be due to the different mobility of the different

parts of the rib and to the elasticity and adaptional capacity of the rib In addition to lateral deviation fixation usually also caused curves in the sagittal plane either kyphosis or lordosis depending on how the new forces were applied

The development of structural changes in experimental scoliosis may be ascribed to the altered balance of forces caused by the surgical procedures In this connexion certain facts relating to the transformation of soft parts and bones should be recalled Soft parts are shortened when the distance between their points of attachment is shortened for a sufficient length of time and extended when the opposite is the case (LANGE) According to STEINDLER both muscles fasciae and ligaments may undergo structural changes if their loading is altered for a sufficiently long time or sufficiently radically These rules afford an explanation for the development of the contractures seen in the present material

According to WOLFF's law both the structure and the shape of bones are influenced by the forces to which they are exposed and in this process both static and dynamic (muscular) forces play a part (CAREY GEISER & TRUETA JANSEN) Opinions concerning the effect of changes in compression and tension on bone growth are controversial but it is generally believed that at least a markedly increased pressure usually leads to retardation (BLOUNT & CLARKE GELBKE HAAS HUETER NACHLAS & BORDEN STROBINO & al VOLKMANN) and reduced pressure to acceleration of growth (ARKIN & KATZ CHILLINI HUETER MULLER VOLKMANN) Increased distension too may result in accelerated growth (RING SMITH & CUNNINGHAM) Decreased loading may cause osteoporosis increased loading osteosclerosis (WEINMANN & SICHER From the changes observable in the present study it may be concluded that the operations resulting in scoliosis caused increased pressure on the concave side of the spine and decreased pressure or distension on the convex side

On the basis of what has been stated above it may be assumed that the forms of experimental scoliosis described in this paper developed in the following way

By various operations an imbalance of the forces acting on the spine was caused either by the reduction of forces on one side (transection or resection of structures) or by the introduction of new forces (fixative operations) The imbalance immediately led to development of scoliosis (except after fixative operations) resulting in increased pressure on the vertebrae and decreased loading on the soft parts on the concave side of the curve and reduced pressure or distension of the vertebrae and stretching of the soft parts on the convex side The altered

loading soon brought about simultaneous adaptational changes of different bones and soft structures in the spine and its vicinity clearly demonstrable as early as one day after operation Owing to the altered position of the spine and the altered loading contractures of the soft parts on the concave side of the curve and extension and as a rule gradual compensatory hypertrophy of the soft parts on the convex side ensued Increased pressure on the vertebrae led to retardation of the longitudinal growth atrophy of the cranial epiphyseal nuclei and cartilage plates in particular and increased sclerosis and increased lateral apposition (a compensatory phenomenon) of the vertebrae on the concave side of the curve while reduced pressure or increased tension on the convex side led to increased longitudinal growth porosis and increased resorption of the vertebrae The further development of the condition depended on the interaction between the factors resulting in scoliosis the compensatory phenomena due to reflexes and the secondary structural changes

VI SUMMARY

The purpose of the present study was to throw light on the mechanism of development of experimental scoliosis

The results are based on observations made after different operation on a total of 800 rabbits and 66 pigs

In order to study the influence of different structures on the position of the spine various operations were unilaterally performed on different skeletal parts muscles ligaments and nerves in the spine and its vicinity (Table I page 16)

Initial functional scoliosis resulted after some of these operations involving the dorsal ends of ribs lumbar transverse processes muscles and/or ligaments attached to them or intercostal muscles (Table II page 21) The primary curve in functional scoliosis was invariably convex towards the side of operation

Transection of the external and dorsal portions of the intercostal muscles was found to be much more effective a procedure in provoking scoliosis than transection of any other portions of these muscles (Tables V—VIII pages 26 and 27)

The functional scoliosis provoked by the different operations always disappeared completely if the animal was subjected to deep anaesthesia or was killed within a few hours after operation This shows that it was due to active muscular force

The greater the number of structures unilaterally removed or cut the loss of function of which had been found to provoke functional scoliosis the severer was the scoliosis resulting (Table IX page 29)

Functional scoliosis provoked by one of the different operations could be straightened or transferred to the other side when one or more of the procedures found to produce scoliosis was carried out contralaterally to the first operation (Table X page 30)

Thus the position of the spine could be influenced by surgical procedures both qualitatively and quantitatively

The forms of functional scoliosis in the present material exhibited one or more compensatory secondary curves No definite rotation of vertebrae occurred and after thoracic operations drooping of the ribs was a common finding on the convex side of the curve (Fig 1 page 22)

Lateral flexibility of the spine showed immediate changes after all operations provoking functional scoliosis (Fig 4 page 31) On flexion towards the intact side the primary curve exhibited greater flexibility than normal but the curve was rigid and became only incompletely straightened by flexion towards the side of the operation Post mortem the changes in lateral flexibility disappeared almost completely which shows that they were mainly due to active forces

When scoliosis was produced in growing animals the condition usually changed throughout the period of growth Sometimes it showed complete regression while in other cases permanent structural scoliosis developed (Figs 5 and 6 pages 36 and 37) The course was found to depend on various factors *e g* healing and regeneration of the injured tissues and postoperative cicatrization Cicatrization in particular seemed to play an essential part inasmuch as it often completely compensated for removed or cut structures The development of structural scoliosis was not directly related to the degree of the initial scoliosis produced by operation Complete regression of the condition occurred in some cases after all thoracic operations except *resection of the dorsal ends of ribs and transection of both costotransverse* ligaments and intercostal muscles (Table XII page 40)

After all those operations which induced functional scoliosis structural scoliosis certainly resulted in some cases (Tables XI and XII pages 38 and 40)

Various fixative operations using nylon thread resulted in structural scoliosis Fixation of ribs to each other and of transverse processes to each other led to scoliosis in some cases Severe progressive scoliosis developed only when spinous processes were fixed to ribs situated several levels cranially or caudally of them and the threads were applied to the ribs near their tubercles (Figs 11 and 12 pages 50 and 51) The greater the growth potency of the region involved by fixation the severer was the scoliosis resulting

The forms of functional scoliosis resulting from the operations here described were sustained by active muscular forces Even when the position of the spine had been changed for one day only structural changes of both vertebrae discs muscles and ligaments were observable (Figs 15 and 23 pages 54 and 67) The soft parts were compressed on the concave side and extended

on the convex side of the curve In the spine shortening of the annuli fibrosi and somewhat increased sclerosis of the vertebral bodies were discernible on the concave side of the curve while on the convex side the annuli fibrosi were somewhat extended The nuclei pulposi were displaced towards the convex side of the curve

The changes increased steadily and simultaneously in both the soft parts bones and cartilage and the following results were usually recorded

The scoliosis became gradually more and more rigid with interbody fusion of vertebrae sometimes resulting

Rotation of the vertebrae as a rule increased steadily as long as the scoliosis progressed and was always directed towards the convex side of the curve *No definite correlation was observable between the degree of lateral* deviation of the spine and rotation The rotation is influenced by appositional and resorptional processes building the vertebrae back towards the mid line

Lordosis or kyphosis of the spine was a common finding at the primary curve If the rotation of the vertebrae is taken into account lordosis was more frequent in the thoracic spine while kyphosis occurred more often in the lumbar spine

In thoracic scoliosis rib humps occurred as a result of adaptional changes mostly a dorsal hump on the convex side of the curve and a ventral hump on the concave side (Figs 13 and 14 page 52)

The extent of deformation of the different vertebrae was found to be dependent on their situation in relation to the scoliosis The greatest changes were seen at the apex of the primary curve

Increased longitudinal growth and porosis of the vertebrae were observable on the convex side of the curve impaired osteogenesis and chondrogenesis on the concave side (Fig 20 and 23—28 pages 64—75)

Marked atrophy of the vertebral bodies was seen on the concave side of the curve particularly in the cranial epiphyses The neurocentral junctions were narrower and fused earlier on the convex side than on the concave side of the curve (Figs 18 and 19 page 61 and 62)

Both macroscopic inspection measurement and marking of *growing* vertebrae and histological studies showed that the vertebrae — body as well as arch — exhibited markedly accelerated lateral growth (increased apposition) on the concave side of the curve and decreased lateral growth or increased resorption on the convex side (Figs 18—22 pages 61—66)

The changes observable on the soft parts may be accounted for by the rules relating to the transformation of soft parts after altered loading and

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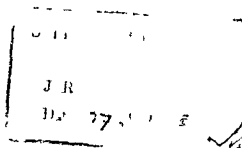
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SOINI RYÖPPY

Transplantation of Epiphyseal Cartilage and Cranial Suture



TRANSPLANTATION OF EPIPHYSEAL CARTILAGE AND CRANIAL SUTURE

ACTA ORTHOPAEDICA SCANDINAVICA
SUPPLEMENTUM no 82

FROM CHILDREN'S HOSPITAL, UNIVERSITY OF HELSINKI, FINLAND
HEAD: PROFESSOR NILO HALLMAN, M.D.,
CHIEF SURGEON: MATTI SULAMAA, M.D.

TRANSPLANTATION OF EPIPHYSEAL CARTILAGE AND CRANIAL SUTURE

EXPERIMENTAL STUDIES ON THE PRESERVATION OF THE GROWTH CAPACITY IN GROWING BONE GRAFTS

by

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ACADEMIC DISSERTATION
To be publicly discussed by permission of the Medical Faculty in the University of Helsinki in lecture room XII on May 26th 1965 at 12 o'clock noon

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— il faut observer sans cesse et reflechir longuement aux donnees de l'observation. Reflechir pour corriger ce que Valery a appele l'etonnante inexactitude probable de l'observation immediate, le faux qui est l'œuvre de nos yeux, car, ajoute-t-il, observer, c'est pour la plus grande part imaginer ce que l'on s'attend a voir. Il y a en somme, apres l'observation, un travail necessaire de l'esprit qui fournit la matiere sur laquelle va s'exercer la recherche experimentale verificatrice.

RENÉ LERICHE

(La chirurgie discipline de la connaissanse, P. 202.)

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Helsinki October 1964

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CONTENTS

I INTRODUCTION

When at the end of the 19th century transplantation of bone began to develop into an important method of treatment the need for a bone graft which would continue its growth after transplantation became evident A search for suitable material was begun because in growing bones the replacement of bone defects with the usual transplants resulted in recurrence of the deformity even when the correction had been temporarily successful

The experimental results of some pioneering workers as long ago as the 18th century showed that the growth in length of the long bones took place in the epiphyses Hence transplantation of the epiphysis should have solved the problem Experimental work done during the first decades of this century however showed that the problem was much more difficult than had been expected The results of animal experiments have been very inconsistent and so far they have not provided a very clear picture of the possibilities of transplantation of the epiphyseal cartilage Yet some results suggest that such transplants may be successful in favourable circumstances What is the reason for so many conflicting results? What is the maximal growth potential of the graft? It is evident that many of the factors contributing to the successful results are still unknown

From the point of view of preservation of growth several clinical attempts to transplant the epiphysis have not been encouraging On the other hand the results of other methods of treatment have mostly not been satisfactory either The tendency in the treatment of congenital bone defects of the extremities is to begin it as early as possible to prevent secondary deformities Because of the increasing number of patients in the youngest age group and the increasing standards expected the problem of the treatment of these cases is becoming increasingly urgent

The epiphyseal cartilage graft has been the only type of growing bone graft experimented on hitherto Only autogenous grafts have shown any tendency to continue growth This limited source of grafting material is one of the disadvantages of the epiphyseal grafts These considerations led the author to attempt to find a new type of growing bone graft As one such possibility calvarial bone including the cranial suture was chosen The growth of the

calvarium takes place at the sutures by proliferation of the sutural connective tissue and successive apposition of bone This growth is analogous to the endochondral growth of the long bones but as a histological process it is far simpler Because the transplantation of connective tissue is relatively easy it was anticipated that the preservation of growth capacity would be possible In the previous literature the author has not found any report of the transplantation of cranial sutures in the sense of growing bone transplants

As regards the clinical applicability of such a procedure we know that the regenerative capacity of calvarial bone is very considerable in infants This makes the taking of the grafts possible without risk

The present work is divided into two parts the transplantation of the epiphyseal cartilage plate and of the cranial suture In both these groups the main focus of interest of the study was the persistence of the growth capacity of the transplants The growth of the grafts was followed radiographically and the specimens were examined by radiological and histological methods

II TRANSPLANTATION OF EPIPHYSEAL CARTILAGE

REVIEW OF THE LITERATURE

EPIPHYSEAL CARTILAGE PLATE AND THE GROWTH OF LONG BONES

In 1727 *Hales* published the results of an experiment in which he drilled holes in the tibia of the chicken and observed that the growth in length took place at the ends of the bone By feeding experimental animals with madder *Duhamel* (1742) was able to show that the bone formed during the madder feeding was coloured red and situated in the metaphysis and in the superficial layer of the diaphysis He drew the conclusion that longitudinal growth takes place at the end of the metaphysis and growth in thickness by apposition on the diaphysis *Duhamel* also fixed nails in the legs of growing pigeons and confirmed the observation of *Hales* *Hunter* (1779) with his well planned experiments confirmed the foregoing results As a conclusion to his experiments with madder feeding he stated that longitudinal growth occurred at the epiphyseal cartilage plate (ECP) He emphasized that a continuous remodelling takes place in bones by resorption and deposition of bone The experiments of *Flourens* (1842) confirmed the previous conclusions

Strelzoff (1872) *Gudden* (1874) *Wolff* (1892) *Thoma* (1915) and *Policard* (1930) considered the interstitial growth of bone to be possible under certain circumstances Others however including *Kölliker* (1851) *Humphry* (1861) *Wegner* (1874) *Schwalbe* (1876) *Haas* (1926) *Gatewood* and *Mullen* (1927) and *Trotzky* (1932) were of the opinion that the longitudinal growth of the tubular bones does not take place interstitially but depends on endochondral growth in the ECP

Later the question of interstitial growth became more complicated when several workers noticed that the mass of bone formed after fusion of vertebral bodies could grow in length (*Biscard* and *Musselman* 1940 *Hallock et al* 1957 *Risser* 1956 *Cleveland et al* 1957 and *Johnson* and *Southwick* 1960) Yet as the results of *Johnson* and *Southwick* show this phenomenon can certainly be explained by factors other than the interstitial growth of bone

Korneu (1929) placed circular metallic markers in the diaphysis of the long bones of rabbits and dogs and found that the distance between these markers increased continuously during growth From this observation he drew the conclusion that the growth of long bones is interstitial in character the epiphyses having only a stimulating and regulating function

The opinion now generally accepted is that the growth in length of the long bones takes place at the ECP It could even be said as *Sissons* (1956) put it the rigid nature of calcified bone tissue makes its interstitial growth impossible

The type of bone formation in the ECP is called endochondral ossification (*Maximou* and *Bloom* 1948 *Ham* 1953 *Sissons* 1956 *Trueta* and *Morgan* 1960) The general histological features of this process were first adequately described by *Muller* (1858) In fact many different processes i e the interstitial growth maturation calcification death and disintegration of cartilage and the formation calcification and destruction of bone are taking place in this area simultaneously (*Ham*) This is also reflected in the microscopic structure of the ECP which can be divided into various zones

The resting zone or germinal layer is situated immediately under the bone plate which separates the ECP from the epiphysis It consists of amorphous material in which scattered cartilage cells are present

The proliferation zone consists of longitudinal columns of cartilage cells arranged in close order and flattened against each other In this zone mitotic figures are seen

The zone of hypertrophic or oedematous or maturing cells is a direct continuation of the columns in the proliferation zone The cells are large spherical or cuboid and oedematous with a central nucleus The cells of this zone produce phosphatase which brings about the calcification of the intercellular substance

The zone of degeneration and calcification In this zone osteoblasts from the metaphysis invade the disintegrating cartilage cells and deposit bone

In the intercellular substance amorphous in the resting zone the collagen fibres arrange themselves parallel to the columns at the level of the proliferation zone More distally the space between the columns becomes very narrow and the calcification of the intercellular substance begins at the level of the last oedematous cells

The thickness of the ECP is related to its activity At birth calcification of the epiphysis has not begun in most bones When the bone plate forms the proximal margin of the ECP becomes visible radiologically In the proximal epiphysis of the fibula of the rabbit this takes place between the tenth and fifteenth day of age (*Heikel* 1959) There is also a constant relation between the number of cells of the ECP and its activity (*Trueta* and *Morgan* 1960) For

instance in the three month old rabbit the number of cells in a column of the proliferation zone in the proximal FCP of the tibia is 10–20 but in the vertebral epiphysis only 6–8

The zone of calcified cartilage also referred to as the primary spongiosa is the site of progressive deposition of bone Distal to it longitudinal bony trabeculae which show inclusions of cartilage matrix are seen In this extensive remodelling takes place and this area is called secondary spongiosa

With age the ECP becomes narrower and the number of cells decrease The time of fusion of the various epiphyseal plates is different According to *Heikel* (1959) the fusion of the proximal ECP of the rabbit fibula takes place between 150 and 225 days of age

In the ECP no perforating vessels such as might be of importance for the nutrition of the cartilage cells are found (*Nussbaum* 1925 1926 *Hurrel* 1954 *Marneff* 1951 *Trueta* and *Morgan* 1960) although some investigators have noted channels in it the function of which is not clear (*Lexer et al* 1904 *Schulze* 1955) *Hurrel* has reported the presence of blood vessels traversing the ECP of the human foetus The vascularization of the ECP has recently been studied in detail by *Trueta* and *Little* (1960) and *Trueta* and *Amato* (1960) According to them the nutrition of the germinal layer and possibly of most of the ECP takes place by way of the vessels perforating the bone plate from the epiphyseal side These vessels are branches of arteries which penetrate the epiphysis close to the capsular insertion near the ECP The function of the metaphyseal vessels is related to the calcification of the cartilage matrix the resorption of the degenerated cells and the laying down of lamellar bone They are of no nutritonal importance even to the hypertrophic cells Experimental ischaemia of the ECP induced by local arrest of nutrition from the epiphyseal side resulted in disturbance or arrest of growth The arrest of nutrition from the metaphyseal side caused disturbed growth in only a few cases

RELATIVE GROWTH OF DIFFERENT EPIPHYSEAL CARTILAGE PLATES

Hales (1727) had already noted that growth was not equal at the two ends of the long bones *Duhamel* (1742) noticed in his experiments on pigeons that the proximal end of the tibia grew more than the distal end

After inserting metallic markers in the bones of rabbits and chickens *Ollier* (1867) came to the conclusion that in the forelimb the epiphyses near the elbow grew very little compared with those situated farther from it In the hindlimbs on the contrary the epiphyses situated near the knee grew the most *Ollier* drew attention to the fact that the growth ratios of the epiphyses were different in

different species of animals In the rabbit the growth ratio of the proximal and distal ECP of the tibia was 25 15 He also refuted with experimental proof the argument of some previous authors that the distal ECP of the fibula grew more than the proximal one In his experiments the ratio was the same as in the tibia On resecting one of the two epiphyses of the long bone *Olher* noticed that the remaining epiphysis could grow more than normally i e partially compensate for the growth of the lacking epiphysis

In 1915 starting from the hypothesis that the nutrient vessel around which *the development of the long bone begins retains its original position as the* central point of the medullary cavity *Digby* performed measurements on human long bones According to him the growth ratio of the proximal and distal ECP of the tibia was 57 43 and of the ulna 19 81

Bergmann (1929) measured the growth of different epiphyseal cartilage plates *in human subjects using the lines of arrested growth*, *which were seen in* radiographs of patients treated with phosphorus containing cod liver oil or ultra violet light The ratio in both the tibia and fibula was proximal ECP distal ECP = 15 12

Using metal markers on dogs *Bergmann* reported equal growth in the proximal and distal epiphyses of the tibia

Payton (1933) used madder feeding on pigs paying special attention to the division between the longitudinal growth of the ECP and that of the epiphysis When the bone plate between the ECP and the epiphysis has formed the ECP can no longer contribute to the growth of the epiphysis but the growth in length of the latter may continue by proliferation of the articular cartilage This must be distinguished from the longitudinal growth of the diaphysis i e of the ECP The growth ratio between the proximal and distal ECPs was 17 16 in the tibia and 15 7 16 4 in the fibula The growth of the proximal epiphysis of the fibula was correspondingly greater

Using metallic markers on the rabbit *Silfverskiold* (1934) found the proximal distal growth ratio in the tibia to be 14 10 He also noticed the possibility of compensatory growth if the growth of one of the two epiphyseal plates was disturbed

Bisgard and *Bisgard* in 1935 placed steel shot in the bones of three goats and obtained for the proximal distal growth of the tibia the ratio 42 52 and in the foetal period (measured from the lines of arrested growth caused by phosphorus feeding) 49 51

[illegible] 1960) in his experimental work on the rabbit used *Silfverskiold's* [illegible] [illegible] [illegible]ations of the growth of the fibula taking into consideration th[illegible] [illegible] [illegible] fibula grows less than the proximal ECP of the tibia

[illegible] (1962) analysed the lines of arrested growth in thre[illegible] patient[illegible] [illegible] [illegible]d not pay attention to the amount of growth but

measurement of the growth from the X ray pictures published in their paper gives the ratio proximal ECP distal ECP = 6 7 in both the tibia and the fibula

Anderson et al (1963) used lines of temporarily arrested growth seen at the ends of the diaphyses of long bones of children for calculation of the growth of different epiphyses The growth of the proximal end of the tibia between ten and fifteen years of age was 57 per cent of the total tibial growth

Summary and comments

In many experimental works the longitudinal growth of the epiphysis has been included in the longitudinal growth of the bone Histologically this is replacement of the interstitially and appositionally growing articular cartilage by bone (*Payton* 1933 *Weinmann* and *Sicher* 1947 *Ham* 1953) and should be distinguished from longitudinal growth of the ECP Some common features are seen in the relation of the growth between the different epiphyseal plates but the ratios reported by different authors differ even in the same animal species The reports on the relative growth of the proximal and distal ECP of the fibula compared with those of the tibia seem to vary

EXPERIMENTAL TRANSPLANTATION OF THE EPIPHYSEAL CARTILAGE

The history of the transplantation of the epiphyseal cartilage plate (ECP) is closely connected with the history of bone transplantation

According to *Peer* (1955) the first successful transplantations of bone were performed in the beginning of the 19th century *Ollier* (1867) was one of the first to examine bone grafts systematically When in the rabbit he resected the epiphyseal end subperiosteally he observed complete regeneration and considerable growth after the operation Total excision of the epiphyseal cartilage resulted in the arrest of growth In the rabbit and the dog *Ollier* transplanted whole bones subcutaneously and into other tissues He reported that in rabbit the grafts remained viable and in the young rabbits he observed some growth in thickness in the transplanted metatarsal bones Longitudinal growth was never seen and no proliferation in the ECP either In young dogs the grafts were resorbed *Ollier* was the first to divide the grafts into auto homo- and heterografts He considered that part of the cells in autogenous bone grafts remained viable

Rudneu (1880) *Radzimousky* (1881) and *Barth* (1893 1894) concluded that all the cells of the bone graft die and the graft is replaced by host tissue

The first reported transplantations of the ECP were made by *Helferich* in 1899 On a young rabbit the distal ECP of the ulna with a thin layer of bone on both sides was detached and reimplanted Some amount of growth was observed but the growth was inadequate and resulted in deviation of the wrist The material was examined histologically by *Enderlen* (1899) He concluded that the reimplanted ECP retains a large part of its vitality The cells situated near the perichondrium and the encoche withstood the transplantation best The central part of the ECP became necrotic Some days after the transplantation an intracellular oedema of the cartilage cells was noticed which was also visible macroscopically as a thickening of the ECP

In the rabbit *Zoppi* (1900) performed both auto homo and heterotrans plantations In autografts he observed formation of new bone and interpreted the result as good from the point of view of preservation of growth In homo grafts similar changes were not seen and the heterografts were resorbed The conclusion drawn by *Galeazzi* (1907 from his auto and homotransplantations was that growth stopped in most cases the cells of the ECP died and the ECP became ossified In some cases there was slight regeneration but it was so inadequate that growth remained seriously disturbed

In 1911 *Wrede* to confirm the clinical experiences of *Lexer* performed so-called transplantations of a half joint in rabbits The whole epiphyseal end of the bone was transplanted but it never remained viable

Axhausen (1912) tried to clarify the absolute transplantability of the ECP Using rats and rabbits he transplanted epiphyseal ends of bones to soft tissues of another animal of the same species In histological examination he noted that a part of the superficially situated cells remained viable Some ossification was also seen in these parts *Axhausen* drew the conclusion that the ECP is transplantable in a histological sense but that regeneration is inadequate for clinical purposes

Using the metatarsophalangeal joint with a part or the whole metatarsal bone as the graft *Borst* (1912) performed reimplantations and homogenous transplantations in the rabbit Growth was seriously disturbed in all cases but in reimplants he noticed some growth The homografts did not grow Con cerning his homotransplantations of the knee joint in the rabbit *Dalla Vedova* (1912) reported that in no case had histological healing occurred

In rabbits aged two months *Rehn* and *Wakabayashi* (1912) homotrans planted the proximal end of the radius to the corresponding site into another animal of the same litter The fate of the grafts was followed histologically after observation periods of different lengths There was good union between the graft and the host bone no central necrosis or cellular oedema of the ECP was seen Aft weeks changes indicative of arrest of the growth appeared

The authors concluded however that growth continued undisturbed and considered clinical homotransplantation of ECP to be justified

v *Tappeiner* (1913) observed some growth in his reimplants which consisted of the distal end of the metarsal bone of the dog The homografts did not grow

Heller (1914) began his experiments in 1911 in these he endeavoured to ascertain the extent to which the growth in the ECP graft was preserved On rabbits aged 4—8 weeks he reimplanted the distal end of the ulna In none of his cases was normal growth seen the shortening was 1/13 of the total length of the bone in the most successful cases In homografts the shortening was more pronounced *Heller* also made four experiments on goats In the reimplantation of the distal end of the radius the shortening was 1/3 of the total length of the bone The results of the histological examination corresponded to those of *Enderlen* in the reimplants The cells in the homografts on the other hand all died

Minoura (1914) transplanted metatarsophalangeal joints of the rabbit as auto and homografts into subcutaneous tissue muscle liver and the peritoneal cavity A number of cells in the superficial parts of the graft seemed to have survived No organized growth was seen even in the autografts which showed only a kind of scattered proliferation (Wucherung) The graft never became longer — rather the contrary

In 1915 and 1916 *Haas* transplanted the metacarpal bones in the dog either whole or split into two As another type of graft he used the ECP of the same bone The graft included a thin bone plate on either side of the ECP Both in reimplantation and in transplantation into the corresponding site in the opposite leg the growth even in the most successful experiments was only a few millimetres Transplantation in two stages to the adjoining metacarpal bone resulted in considerably diminished growth The author concluded that the ECP is very sensitive as a transplant and that its survival in transplantation is directly related to revascularization

In none of his auto and homogenous transplantations of half joints in rabbits was *Giani* (1916) able to detect any longitudinal growth in the graft *Pucci* (1916) transplanted the cubital joint as a homograft in the rabbit The fusion between the graft and the host bone and likewise the function of the transplanted joint were good

To verify the results of *Rehn* and *Wakabayashi* v *Tappeiner* (1916) made similar experiments He did not distinguish between proximal and distal epiphyseal growth but only measured the total length of the bone There was no shortening of the operated bone even in experiments in which the ECP had changed into connective tissue The author concluded that transplantation had failed in only two cases out of fourteen

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far enough from the ECP He expressed the opinion that the good results obtained by *Heller* and *Fohl* were due to regeneration of the cartilage cell left on the outside of the graft. *Haas* concluded that the ECP loses its capacity for growth after transplantation

May (1934) reimplanted the whole radius of the dog The extraperiosteally removed graft became necrotic but in the subperiosteally removed graft the ECP regenerated The graft grew less than 50 per cent of the control

Selye (1934) removed the distal end of the femur and a the result obtained a new cartilaginous epiphyseal end the cartilage tissue of which resembled that of articular cartilage He reported that growth continued normally

Silfverskiold (1934) tried to fill the gaps in the previous experimental work and to check the uncertain results He performed numerou experiments and in different ways arranged tran plantations of the ECP The pedicle graft grew almost normally but the new bone was thin and not useful for practical purposes When the ECP graft was transplanted into the joint cavity the graft was gradually resorbed. In repeating the experiments of *Heller* and *Fohl* he obtained the ame results as these workers He took great care to ensure that no cartilage celles were left on the outside of the graft Tran plantation of the ECP of the ulna to a segmental defect in the diaphysis of the opposite ulna resulted in gradual ossification of the ECP and no growth was observed. When the same graft was transplanted to it corresponding si e in the opposite limb growth was much more limited than in the reimplant — in the most successful cases about half of the normal. The homografts did not grow The author considered the clinical application of epiphyseal transplantation as pos ible with certain restrictions

Pereira and *Dupertuis* (1936) transplanted pieces of epiphyseal cartilage one cubic centimetre in ize to the diaphy is of the same bone in a young rabbit, a procedure which resulted in the formation of large exostoses

On reimplantation ("isolement) of the distal ECP of the ulna in the rabbit, *Sousa Pereira* (1937) reported considerable growth. The hortening after twelve months was 3—5 mm When the graft was rotated through 180 degrees around its transverse axis the hortening was 8—18 mm the growth of the graft 2—6 mm and the direction of growth toward the diaphysis The author concluded that the graft continued its function in all cases, but changes which resulted in disturbance of the growth were seen

Bisgard (1939) took two slices of cartilage of the distal femoral ECP of the goat, and transplanted them to a segmental defect in the diaphysis of the tibia In three weeks both grafts were ossified In pecimens taken three months later no cartilage cells were seen.

Banks and *Compere* (1941) excised the distal ECP of the femur in the rabbit, which resulted in bony union between the epiphysis and metaphysis *Hellstadius*

(1947) resected the distal end of the ulna with the ECP and a piece of metaphysis and diaphysis. In one of the extraperiosteal resections good regeneration and considerable growth in length were seen. In all cases of subperiosteal resection the ulna grew significantly in length.

Gordon and *Warren* (1918) used as grafting material discs of cartilage taken from the foetal epiphyses of the rabbit. These were transplanted to cortical defects in the diaphysis of adult animals. No formation of exostoses was seen. The cartilage cells lost their capacity for growth even if they remained viable for long periods (twelve weeks in these experiments). *Lacroix* (1951) transplanted pieces of ECP of a young rat beneath the renal capsule of another animal of the same litter. They grew considerably during the observation period of four weeks, forming new bone.

Herndon and *Chase* (1952) noticed that in the reimplants and homotransplants of the knee joint in the dog a number of bone cells of the reimplants survived. The greater part of the graft became necrotic and was gradually replaced by host tissue.

Using the Spongiosatest, *Len* (1955) concluded that all the bone cells died but the soft tissue parts of the graft survived at least partially and preserved their osteogenic capacity. As little as two days after transplantation part of the graft made contact with the host circulation. The surviving cells of the graft participated in the process of creeping substitution of the graft.

Peer (1955) in his survey of the literature concerning the transplantation of the ECP pointed especially to the disagreement among investigators regarding the long term survival of the ECP after transplantation. He concluded that the fate of the epiphyseal cartilage in autogenous and homogenous transplants and the capacity of the cartilage to grow are surrounded with considerable doubt.

Using rabbits, *Ring* (1955[1]) examined the regeneration after total and partial excision of the distal ECP of the ulna and noticed that the ECP could regenerate transitorily in some cases even after total excision. The ECP became ossified in most cases. The same author (1955[2]) also reimplanted the ECP after rotating it 180 degrees around its transverse axis. Some of the reimplants showed almost normal growth. In the latter group growth was poor and ceased 6–8 weeks after transplantation. In transplantation of the ECP to the corresponding site in the opposite leg (*Ring* 1955[3]) 5 out of 18 experiments were interpreted as successful. All homografts failed to grow. The author concluded that the application of epiphyseal transplantation in clinical practice was justified but pointed out that there is no ready source of autogenous epiphyseal cartilage for grafting material.

Betzel in 1956 transplanted tubular bones of newborn puppies to the dorsal musculature of adult dogs and noticed that the grafts were totally resorbed No formation of new bone was seen

In the experiments of *Schneider* (1956) where the ECP of the newborn rabbit was transplanted to a segmental defect in the diaphysis of the radius of a young rabbit enchondral ossification, but no significant growth was seen in the graft Bony union was achieved but the graft seemed to disturb the consolidation rather than to promote it.

In puppies *Schraiber* (1956) transplanted the proximal end of the fibula to the site of the excised epiphyseal end of one of the bones of the foreleg The graft included a relatively long piece of diaphysis The maximal growth of the graft was 153 per cent of its original length The rapidity of growth depended on the general growth rate of the animal being greater in an actively growing bone In microscopic examination the author noticed that all osteocytes and cartilage cells died A number of cells in the perichondrium periosteum and epiphyseal cartilage survived Towards the end of the first month after trans plantation the graft was restituted and enchondral growth in the ECP was in process

Felts (1957) reported that in the transplantation of whole isologous and homologous bones to the subcutaneous tissue on mice aged two days the growth of the isografts was 80 per cent of the normal while the growth of homografts ceased 12—16 days after transplantation

On 2 to 29 days old rabbits *Heikel* (1959 1960) tran planted the proximal epiphyseal end of the fibula as an autograft to the site of the radius which had been totally or partially removed The transplantation was performed as a one- or two stage operation The growth was in most cases measured from a piece of metal wire inserted in the diaphysis In the best cases the longitudinal growth of the graft was 2/3 — 8/9 of the growth of the ulna and about 1/2 — 2 3 of the growth of the control ECP of the fibula In one series the ame type of graft was implanted into the thigh The growth of this varied between 1/8 and 1/2 of the growth of the fibula About half the grafts were fused side to side with the femur The experiments were carried out on animals of different ages even on very young animals but no definite correlation between the age of the animals and the growth of the graft was seen In histological examinat ion the author noticed that the central part of the ECP underwent necrosis but a thin peripheral layer of the reserve zone survived transplantation The ECP regenerated from the surviving parts This process cut off the region of the necrotic cartilage and islets of this were visible up to 23 days after trans plantation in the diaphysis at a distance which corresponded to the growth of the graft as measured on radiograms

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Using rabbits *Ring* (1955[1]) examined the regeneration after total and partial excision of the distal ECP of the ulna and noticed that the ECP could regenerate transitorily in some cases even after total excision. The ECP became ossified in most cases. The same author (1955) also reimplanted the ECP after rotating it 180 degrees around its transverse axis. Some of the reimplants showed almost normal growth. In the latter group growth was poor and ceased 6–8 weeks after transplantation. In transplantation of the ECP to the corresponding site in the opposite leg (*Ring* 1955[3]) 5 out of 18 experiments were interpreted as successful. All homografts failed to grow. The author concluded that the application of epiphyseal transplantation in clinical practice was justified but pointed out that there is no ready source of autogenous epiphyseal cartilage for grafting material.

(*Heller* 1918 *Silfverskiold* 1934 *Sousa Pereira* 1937 In these reports the amount of growth compared with the normal was not shown in a convincing manner it is true The results obtained by *Haas* (1931) for the same type of trans plantation were negative but his material consisted of only a few scattered experiments The reimplantation of the ECP of the metatarsal and metacarpal bones did not give a positive result from the point of view of preservation of growth (*Minoura* 1914 *Haas* 1915–16 *Segale* 1917)

The proximal ECP of the fibula seems to have given positive results even when a part of the diaphysis was transplanted with it (*Schraiber* 1936 *Heikel* 1960) The ECP when transplanted to a defect in the diaphysis did not continue to grow but became ossified (*Silfverskiold Sousa Pereira Bisgard* 1939) When transplanted as a free graft to the soft tissues the ECP did not preserve its capacity for growth (*Ollier Minoura Axhausen Heller Silfverskiold*) Only *Heikel* noticed some growth in this type of graft When the ECP was rotated 180 degrees around its transverse axis it showed some amount of growth in the opposite direction (*Heller* 1918 *Sousa Pereira Ring*) As a pedicle graft the ECP grew almost normally (*Reschke* 1929 *Silfverskiold*)

In no cases has the transplanted ECP grown as much as it would have done in its original site

It seems to be histologically established that a part of the cells of the trans planted ECP survive (*Enderlen* 1899 *Segale Heller* 1918 *Schraiber Heikel* Some of these cells certainly play a very important role in the regeneration of the graft The survival of the resting zone of the ECP seems to be of the utmost importance for the preservation of growth capacity (*Heller Ring Heikel*)

CLINICAL TRANSPLANTATION OF THE EPIPHYSEAL CAPTILAGE

On clinical material *Ollier* (1867) performed a number of resections of epi physeal ends and whole joints He reported that subperiosteal resection of the epiphyseal end often resulted in good regeneration and even some longitudinal growth in length of the resected epiphysis

Zoppi (1902 1905) reported a case of a 12 year-old patient in whom he had transplanted a piece of the distal epiphyseal end of the fibula to the site of the distal end of the tibia which had been destroyed by osteomyelitis The ECP was clearly visible in radiographs 2 months after the operation

Galeazzi (1907) used a thin plate consisting of the distal ECP of the humerus as a graft This was in two cases transplanted to the distal end of the shortened radius The graft necrotized

Lexer (1908 and 1913) *Borst* (1912) *Kuttner* (1915) *Capurro* and *Pedemonte* (1935) among others used fresh homogenous grafts which consisted of whole

bones epiphyseal ends or whole joints In many cases the grafts fused well and no resorption was noticed macroscopically By 1920 *Lexer* had given up using homografts and recommended only autografts in this type of trans plantation In some ca es *Kuttner* transplanted a growing epiphyseal end of a monkey to his patients He reported a case in which the fibula of a monkey had been transplanted to the site of a congenitally lacking fibula One year and eight months later no resorption was visible radiologically but there was no growth in the graft The LCP was clearly visible

In a child aged 7 years *Saar* (1913) transplanted the proximal end of the fibula to the site of the excised distal end of the radius Regarding the same case *Heller* (1914) later reported that one and a half years after the operation there was no growth in the graft although the ECP was radiologically visible

On the basis of these previous experiences *Axhausen* (1919) regarded the pedicled graft as the only possibility for successful transplantation In a child the distal end of whose radius was destroyed by tuberculosis he transplanted half of the distal end of the ulna to the site of the former in two stages 4 years later the distal ECP of both the radius and the ulna had grown 9 mm *Axhausen* performed a similar operation in a case of total defect of the radius 12 years later he wrote to *Silfverskiold* (1934) that the cases had remained good *Axhausen* also tried to transplant the split distal end of the tibia to the site of the missing fibula Because of technical difficulties this became a free graft Six weeks later the graft was removed and examined histologically Only a number of superficially situated cells of the ECP were viable *Axhausen* regarded the possibilities of regeneration and continuation of growth as doubtful

Oehlecker (1922 1923) reported some growth in the phalanx of a toe which had been used as a substitute for the missing proximal phalanx of a finger After 7 years growth of several millimetres had occurred The growth in pedicled grafts transplanted according to the procedure of *Nicoladoni* continued normally in most cases Reimplantation of the distal end of the radius resulted in cessation of growth in one case The same author performed 8 free transplantations of the ECP on clinical material and in all of them obtained a negative result He concluded that the pedicled graft was the only type capable of success

In a child aged 4 years *Straub* (1929) transplanted the split distal end of the tibia to the site of a damaged distal end of the opposite tibia 16 years later it was seen that the graft had grown and the shortening had not increased

The idea of using a split tibial graft to correct a defect in the fibula was also tried by *Assen* (1934) He modified it by leaving some tibiotalar ligaments as a pedicle and obtained normal growth in the graft

Starr (1945) observed no growth in the proximal end of a fibula transplanted to the site of the missing distal end of the radius

Henger (1945) substituted the first metatarsal bone by a fibular graft containing the ECP on a 7 year old child The growth of the graft during the following 3 year period was 0 5 cm

In a child aged 11 years *Key* (1949) reimplanted the proximal end of the radius In radiological examination 4 years later the structure and growth of the graft seemed normal

Barr (1954) reported that the distal ECP of the ulna which had been transplanted to a defect in the diaphysis of the radius had grown 2 cm and caused a dislocation of the head of the radius

Peer (1955) buried a supernumerary toe and finger in the abdominal fat and noticed by palpation and roentgenographic examination 22 months later that the bones and cartilage had retained their structure and that the motility of the joints was good

Riordan (1955) used a modified method of *Starr* in the treatment of defects of the radius There was no growth in his 10 fibular grafts Some increase in length was attributed to the ossification of the epiphysis He reported that he had seen some cases of other authors in which clear growth was visible He regarded successful transplantation as possible if the child was young (under 1 year of age) and the graft small enough *Bunnel* (1955) in this connection expressed the opinion that epiphyseal grafts do not grow basing his view especially on the results of *Haas*

Heikel (1959) published the early results of two cases treated by the method of *Riordan* In one of these some growth was visible 11½ months after the transplantation

Sulamaa (1960 1963 1964) transplanted a metacarpal bone to the site of a missing radius and noticed some growth in the graft during the first 2 years after the operation A gradual ossification of the ECP led to cessation of the growth

Riordan (1962) on the basis of clinical experience was of the opinion that large joint transplants will not survive but that there was a change of survival and continuation of growth if small non weight bearing joints or epiphyseal ends are used on young patients

Spira and *Farin* (1964) transplanted the distal ECP of the fibula on a child aged 9 years to a segmental defect in the diaphysis of the same bone After eighteen months the ECP proved to be radiologically open but histological examination revealed complete disorganisation in it The remnants of the ECP appeared as a transverse band of fibrous tissue and cartilage

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TABLE 1 — *Transplantation of the ECP of the fibula A group of control experiments is included in the table*

Type of experiment	Number of experiments Rabbit	Dog
Investigation of normal growth of ECP by using metal markers (control series)		8
Transplantation of ECP to the opposite fibula	8	14
Transplantation of ECP into muscle	6	8
	14	30
Total	44	

OPERATIVE METHODS
(fig 1)

Both the rabbits and the dogs were anaesthetized with ether Most of the dogs were given Nembutal 30 mg/kg I M as premedication The operative field was shaved and washed with two antiseptic solutions successively (Rodalon ® and 1 per cent mercurochrome) The habitual aseptic operative technique was used

Measurement of the proportional growth of the epiphyses of the tibia and fibula To permit the use of the tibia as a control of the growth of the proximal ECP of the fibula a group of control experiments was performed on 4 dogs A transverse metal marker was placed in the diaphysis of both fibula and tibia The distance of the markers from both epiphyseal lines was measured radiographically during growth

Transplantation of the ECP into the corresponding site in the opposite fibula A lateral longitudinal incision was made at the site of the proximal end of the fibula The proximal end of the fibula was exposed and the peroneal nerve separated from it The fibula was cut in the metaphysis by sawing with a thin bladed scalpel The distance from the cut line to the ECP was 3–4 mm on the rabbit and 4–5 mm on the dog The epiphysis was either cut about 2 mm proximally from the ECP or detached as a whole with the graft The freeing was extraperiosteal and extraperichondral At the distal end of the graft a metal marker was attached and in many cases a short stainless steel wire was inserted into the distal end to give better adaptation to the host bone This operation was performed successively in the two legs and the grafts were then interchanged During the procedure the graft was kept in sterile physiological saline solution The incision was closed by interrupted catgut sutures and the

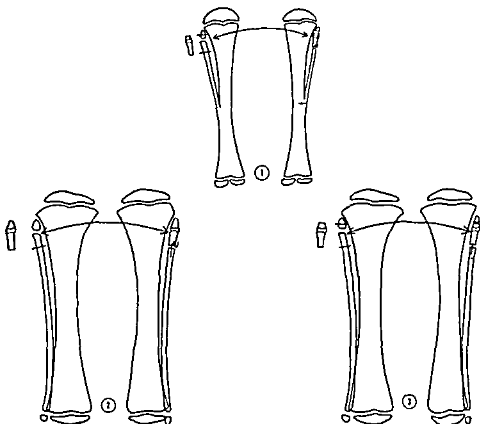


FIG 1 — *Transplantation of FCP Operative methods in the rabbit (1) and in the dog (2 and 3) The graft was excised on both sides successively and the grafts were then interchanged In the pictures only the first part of the procedure is illustrated Note the marking methods In the dog two types of graft were tested*

operative area covered with a plastic film (Nobecutan®) No other bandage or splinting was used

Transplantation of the FCP into muscle A graft of the same type as described above was placed between the peroneal muscles of the same leg In this group the graft was not marked with metal markers

CONTROL METHODS

The length of the graft was measured during the operation and from the specimen after the killing of the animal During the observation time the length of the graft was measured from the radiographs Comparison of the results of the measurements from the graft or specimen and from the radiographs showed that the accuracy of measurement was 0 5 mm

Transplantation to the opposite side The control method was different in the rabbit and the dog

R a b b i t The distal end of the fibula of the rabbit is fused with the tibia The growth of the fibula is therefore dependent on only one ECP As controls both the tibia of the same leg and the fibula of another animal of the same litter were used The latter control was added because it was possible that the graft might disturb the growth of the tibia The distance of the ECP from either the metal marker or the site of fusion of the tibia and fibula was measured To eliminate the error of a possible shifting of the site of fusion which has been suspected by *Heikel* (1960) a metal marker was placed in many cases in the diaphysis of the tibia In fact it was noticed by this method that the site of fusion could be used with sufficient accuracy as the distal point of measurement

The growth of the ECP of the tibia is greater than that of the fibula The result is that during growth the ECP of the fibula moves in a distal direction in relation to the proximal ECP of the tibia This was allowed for by calculating the average distance between the proximal ECPs of the tibia and fibula in a group of rabbits of different ages (see results table 2 p 32) and subtracting the value obtained from the growth of the proximal ECP of the tibia

D o g Two types of controls were also used the growth of the proximal ECP of the tibia of (1) the same leg and (2) another animal of the same litter The latter control was added for the same reasons as in the rabbit In calculating the control value from the growth of the tibia the average obtained in the control experiments was used (see results table 3 p 33) The average value of 51 per cent which corresponds to the contribution of the proximal ECP to the growth of the tibia was used in the calculation The diaphysis of the fibula grows less than that of the tibia The shift of the proximal ECP of the fibula in relation to that of the tibia corresponds to this difference in growth The values showing this difference were obtained by the same method as in the rabbit (see results table 2 p 32) This difference was divided by two (corresponding approximately to the ratio 51 49)

Transplantation into the muscle The control methods were the same as in the foregoing group

RADIOLOGICAL AND HISTOLOGICAL METHODS

X ray examinations During the observation period radiological check ups were made by the usual routine methods The focal distance was 100 cm Special attention was paid to ensure that the whole plantar side of the leg was in contact with the film Some of the animals were anaesthetized with Nembutal before the X ray examination

Radiological examination of the specimen The animals were killed with Nembutal or ether The tibia and fibula and the free grafts in the muscle were dissected out examined macroscopically and placed in 5 per cent formalin solution The radiological examination was made with a special X ray apparatus adapted for the examination of delicate bone structures (ERK 10/50 made by Messrs O Y Havemann A B Helsinki) The voltage and power of the current were modified according to the size and calcium content of the specimens The photographic data for the radiographs of the most delicate specimens were 20 kV 10 m A 20 sec focal distance 50 cm

Histological methods The specimens were decalcified in 5 per cent nitric acid embedded in paraffin cut longitudinally and stained with haematoxylin and eosin for microscopic examination

RESULTS

NORMAL GROWTH OF THE PROXIMAL ECP OF THE TIBIA AND FIBULA

The results of measurement of the average distance of the proximal ECP of the tibia and the fibula at different ages are seen in table 2 In the rabbit the distance increased between the ages of 2 and 28 weeks from 3 mm to 8 5 mm This is the difference in the longitudinal growth of the proximal ECP of the tibia and that of the fibula In the dog the increase between the ages of 3 and 45 weeks was 6 5 mm which is the difference in longitudinal length of the diaphyses of the tibia and the fibula

TABLE 2 – *The distance between the proximal ends of the metaphyses of the tibia and fibula during growth*

Rabbit											
Age (weeks)	2	3	4	6	8	11	15	17	24	28	
Distance (mm)	3	4	4 5	5 5	6	6 5	7	7 5	8	8 5	
Dog											
Age (weeks)	3	4	8	15	17	22	26	28	30	34	45
Distance (mm)	3 5	4	4 5	5 5	6	7	7 5	8	8 5	9	10

The measurement of the longitudinal growth of the proximal ECP of the tibia in [illegible] in the dog gave the results seen in table 3 The average growth of the proximal ECP of the tibia was 50 per cent of its total growth In the fibula the [illegible] tion of the proximal ECP was 52 5 per cent The difference in growth of [illegible] physes corresponds to the results seen in table 2 but as the

growth in millimetres of the proximal ECP of the fibula and tibia are practically the same the relative contribution of the proximal ECP of the fibula becomes slightly greater The value of 51 per cent was used in the calculation because the greater tendency of the markers to turn in the fibula makes it safer

TABLE 3 — *The normal growth of the proximal ECP of the tibia and fibula on the dog*

mal No	Age (weeks)	Side	*Tibia* (mm)					*Fibula* (mm)				
			Length	Growth	Prox length	Prox growth	Growth of prox ECP in %	Length	Growth	Prox length	Prox growth	Gr (pr E in
71	10	d	77		26			72 5		12 5		
	10	s	77		25 5			72 5		25		
	24	d	128	51	5?	26	51	121 5	49	57 5	25	5
	24	s	127 5	50 5	49	25 5	50 5	120 5	48	48	25	5
72	10	d	75		28			70		35		
	10	s	75 5		26			71		12		
	24	d	125	48	5? 5	24 5	51	117 5	47 5	60	25	5
	24	s	123 5	48	50	24	50	117 5	46 5	56	24	5
73	10	d	78		24			75		17		
	10	s	77 5		24			75		22		
	24	d	150	52	50 5	26 5	51	125	50	45 5	26 5	5
	24	s	129 5	52	50 5	26 5	51	122	49	56?	14	(2
74	10	d	78		27			75		43		
	10	s	77 5		26 5			72		50 5		
	24	d	150 5	52 5	54	27	51 5	125	49 5	69	26	5
	24	s	150	52 5	54	27 5	52 5	122 5	50	57	26 5	5
	Average						51					5

) the marker expelled

TRANSPLANTATION OF THE ECP OF THE FIBULA TO THE CORRESPONDING SITE IN THE OPPOSITE LEG IN THE RABBIT

The results are seen in table 4 There was clear growth in 7 out of 8 grafts In 3 cases the amount of growth was comparable to normal The graft had fused to the diaphysis in all except one case Fusion to the epiphysis was noticed in only 3 cases and seemed not to be essential for the preservation of growth The ECP and the radiological density of bone were interpreted as radiologically normal in all well grown grafts A good initial alignment of the graft in the host area seemed to be of significance for the succesful result

In figures 2 and 3 examples of the experiments are seen



FIG 2 – *Transplantation of ECP Rabbit no 173 X ray picture 1 week (1) 9 weeks (2) and 19 weeks (3) after the transplantation The growth of the graft equalled that of the control*

TABLE 4 – *Transplantation of the ECP of the fibula to the corresponding site*

Animal No	Age at operation (days)	Time of observation (weeks)	Growth of *graft* (mm)	Growth of ECP of another animal *(contr I)*	*Growth of graft in % of control I*	Growth of prox ECP of tibia (mm)	Calculated growth of fibular ECP (mm) *(contr II)*	*Growth of graft in % of control II*
112	22	22	19.5	27	*72*	27.5	24	*81*
171	28	19	10	24	*47*	27	23.5	*43*
172	28	19	10	26	*38*	24	20.5	*49*
173	28	19	24	21	*114*	27	23.5	*104*
325 d	28	29	23	27.5	*84*	28.5	24.5	*94*
325 s	28	29	11	27.5	*40*	25	21	*52*
324 d	28	19	21.5	20.5	*105*	25.5	19.5	*110*
324 s	28	19	0	20.5	*0*	17.5	13.5	*0*

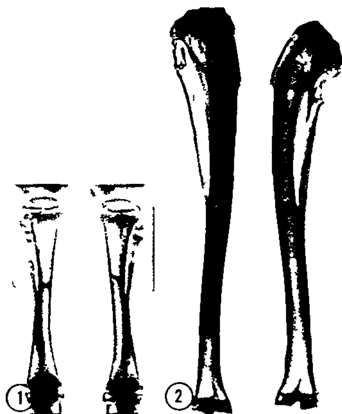


FIG 5 — *Transplantation of ECP Rabbit no 323 The grafts have been interchanged (1) X ray picture after transplantation (2) The specimens Note the metallic markers fo measurement of growth The growth of the graft was 94 per cent of the normal on the right side and 52 per cent on the left*

the opposite leg in the rabbit

Macroscopical and radiological observations					
Fusion of graft to diaphysis	Fusion of graft to epiphysis	Radiol appearance of ECP	Radiol density of bone	Initial alignment of graft	Special observations
fused	not fused	open	normal	satisf	gr ft lender
fused	not fused	partly fused	decreased	poor	bony prom nenc t of fus on w th d phy
not fused	not fused	partly fused	decreased	unsatisf	
fused	not fused	open	normal	good	graft lender
fused	fused	open	normal	good	
fused	fused	fused	normal	good	bone bridge between d aphy of t b nd f bul
fused	fused	open	normal	good	bone bridge as bove
fused	not fused	fused	almost 0	poor	g aft forms an rch-like bridge on t b l d aphys

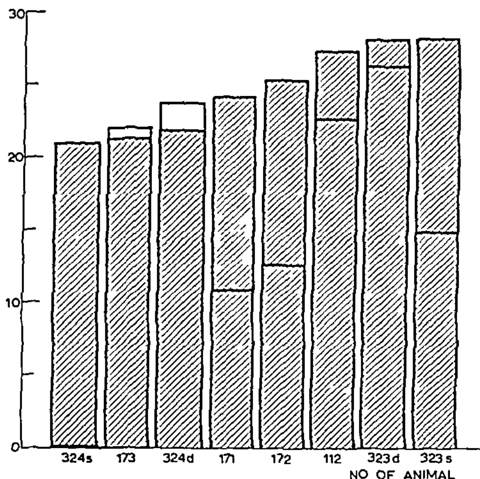


FIG 4 — *Transplantation of the ECP to the corresponding site in the opposite leg in the rabbit The growth of the grafts (the level of transversal lines) as compared with the normal growth of the ECP (hatched columns)*

The growth of the grafts as a percentage of the control growth is graphically illustrated in figure 4

Histological findings

Microscopic examination was made in cases 327 (control) 112 171 172 and 173 *Case 327* (control animal age 33 weeks) See fig 5 The ECP is regular and relatively wide The resting zone is very narrow For the most part its matrix looks homogeneous but in places areas of slight granulation are seen Many of the palisades of the proliferating zone begin very near the bone plate The number of growing cells in the columns varies between 10—15 the number of hypertrophic cells between 3—7



FIG 5 — *Epiphyseal transplant at the corresponding site in the opposite leg in the rabbit Above Normal fibular ECP of a rabbit aged 33 weeks Case no 327 Below The ECP of the transplant in case no 112 Time of observation 27 weeks Note the bony bridge between the epiphysis and the metaphysis*

Case 112 (growth 83 per cent of the control) See fig 5 The ECP is a little narrower than in the preceding case Except for the central part it is mostly fairly regular The columnar arrangement of the cells is not so clear as in the previous case The resting zone looks wider than in the control but areas of granulation or striation are more prominent The other zones of the ECP are relatively narrow The zone of bone

formation looks thin but otherwise normal. As a prominent feature a marked narrowing is seen in the centre of the ECP. In some sections a bony promontory is seen on both the epiphyseal and metaphyseal surfaces of the plate separated from each other only by a thin layer of partly ossified connective tissue. The columnar arrangement of cartilage cells in this area is irregular and scattered.

Case 171 (growth 13 per cent of the control). The ECP consists of scattered short irregular columns or groups of cartilage cells separated by deeply and unevenly staining cartilage matrix. The streaked character of the matrix is very striking. The different zones of normal ECP cannot be distinguished. On a narrow area at the metaphyseal border relatively normal formation of bone is seen.

TABLE 5 — *Transplantation of the proximal ECP of the fibula to the corresponding*

Animal No	Age at operation (days)	Time of observation (weeks)	Growth of *graft* (mm)	Growth of tibia of another animal (mm)	Growth of fibular ECP of another animal (mm) *(contr I)*	*Growth of graft in % of control I*	Growth of tibia of experimental animal (mm)	Calculated growth of fibular ECP (mm) *(contr II)*	*Grow of gr in % of contr*
211 d	45	13	7	79 5	39 5	*18*	81	40	*18*
211 s	45	13	10	79 5	39 5	*25*	82 5	41	*24*
212 d	45	13	26	79 5	39 5	*66*	75	37	*0*
212 s	45	13	15 5	79 5	39 5	*34*	75 5	37 5	*36*
221 s	60	11	21 5	69	34	*63*	68	33 5	*64*
221 s	60	11	22 5	69	34	*66*	67 5	33 5	*67*
222 d	60	11	26	69	34	*76*	76	38	*68*
222 s	60	11	16 5	69	34	*49*	74	37	*45*
241 s	25	22	16	97	47 5	*34*	95	45 5	*35*
246 s	25	22	47	97	47 5	*99*	95	46 5	*101*
334 d	26	27	47 5	98	48	*101*	105 5	50	*95*
334 s	26	27	54 5	98	48	*72*	104	51 5	*67*
335 d	26	27	42 5	98	48	*89*	92 5	44	*97*
335 s	26	27	42	98	48	*87*	91	44	*95*

Case 1/2 (growth 49 per cent of the control) The ECP is thin and irregular and penetrated in the middle by a bony bridge in between the epiphysis and the meta physis A thin resting zone is seen only in some areas The palisades of cartilage cells are scattered short and separated by a deeply staining streaked matrix The zone of bone formation is very narrow or totally lacking

Case 1/3 (growth 104 per cent of the control) Compared with case 527 the graft is thin in diameter The ECP is regular and relatively wide The resting zone is thin or in places lacking and its matrix stains rather unevenly The various zones of the ECP are clearly visible and the columns relatively long containing 10–15 cells The zone of calcification and the metaphysis look normal

site in the opposite leg in the dog

Macroscopical and radiological observations					
Fusion of graft to diaphysis	Fusion of graft to epiphysis	Radiol appearance of ECP	Radiol density of bone	Initial alignment of graft	Special observations
not fused	not fused	fused	greatly decreased	good	
fused	fused	bone bridges	normal	unsatisf	p phys h the form f hourgl
fused	fused	oblique bone bridge	uneven in metaphysis	good	g l t on t th te f f on w th d phys s
fused	not fused	partly fused	normal	poor	
fused	1)	bone bridge	normal	good	
fused	1)	bone bridge	normal	good	
fused	1)	bone bridge	uneven in metaphysis	good	
fused	1)	oblique bone bridge	normal	satisf	
fused	fused	fused	normal	poor	
fused	fused	bone bridge	normal	good	
fused	fused	normal	normal	good	ep phy fl t
fused	fused	uneven	normal	good	p phy fl t
fused	1)	normal	normal	satisf	
fused	1)	normal	normal	good	bone bridg between d a-phys of t b nd f b l

1) the epiphysis was tran planted as a whole

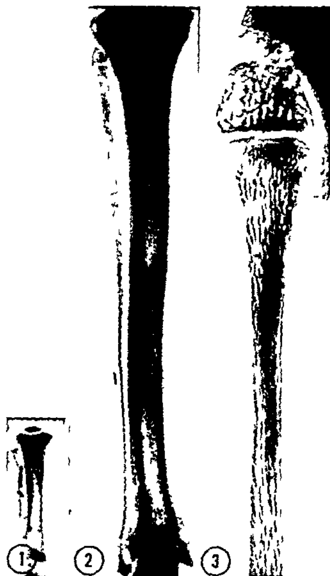


FIG 6 – *Transplantation of FCP Dog no 33J d X ray control after transplantation (1) and after an observation period of 2 weeks (2) (3) Enlarged X ray picture of the specimen The growth of the graft equalled that of the control*

The histological structure of the ECP was normal in one case (175) in which the graft had grown as much as the control In others changes which differed from the normal were seen Among these the narrowness of the ECP and especially of the resting zone the irregular pattern of the cartilage columns and the bony and connective tissue streaks in between the epiphysis and the metaphysis were the most prominent

TRANSPLANTATION OF THE ECP OF THE FIBULA TO THE CORRESPONDING SITE IN THE OPPOSITE LEG IN THE DOG

The results of the transplantation of the ECP in the dog are seen in table 5 The growth of the graft was seen in all 14 experiments In 4 cases the amount of growth was practically normal Fusion of the graft to the diaphysis had taken place in all except one experiment Fusion to the epiphysis was evident in 6 cases but had not occurred in 2 out of 8 cases in which the epiphysis had been cut The ECP was radiologically normal in three cases which had also grown normally In all the other experiments some abnormalities such as unevenness or bony bridges were seen The radiological density of the bone was interpreted as normal in most cases The initial alignment of the graft in the host area was good in the cases where the graft had grown well

In figures 6 7 and 8 some examples of the transplantation of the ECP in the dog are seen

A graphic illustration of the observed growth of the grafts compared with their calculated growth is presented in fig 9

Histological findings

In cases 73 (control) 74 (control) 82 (control) 211 s 212 221 222 334 and 333 histological examination was made

Case 73 (control animal age 28 weeks) See fig 11 The ECP is rather thick and its structure is regular The various zones of the cartilage are clearly distinguished The resting zone consists of about 1/3 of the thickness of the plate Its matrix is homogeneous except for some minor areas of slight granulation or streaking The columns are relatively long consisting of 10—20 cells The columns in the zone of intracellular oedema consist of 3—5 cells and the zone of degeneration is of about the same thickness

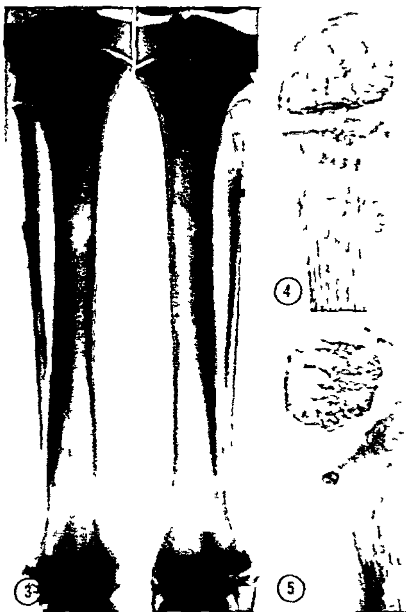
Case 74 (control animal age 28 weeks) The microscopic picture does not differ significantly from case 73

Case 82 (control animal age 21 weeks) The ECP is narrower than in the two foregoing cases and more irregular in character The bone plate is penetrated by numerous blood vessels In some places the resting zone comprises almost half the thickness of the ECP but is totally lacking in others Its matrix shows areas of granulation and weak staining The columnar zone is relatively narrow and the arrangement of the columns slightly irregular The zone of intracellular oedema is relatively higher than in the two foregoing cases

Case 211 s (growth 24 per cent of control) The ECP is of about the same thickness as in case 82 and rather regular The various zones are clearly distinguished The resting zone is seen only in places The cartilage columns are very short and scattered containing only 6—7 cells The matrix shows pronounced fibres throughout the ECP In some sections massive bands of partly ossified connective tissue connect the metaphysis with the epiphysis The zone of intracellular oedema and that of degeneration like the metaphysis look normal



FIG 7 — *Transplantation of ΓCP D]g no 2[illegible]2 The grafts have been interchanged X ray pictures 5 days (1) 5 weeks (2) and 11 weeks (3) after transplantation (4) and*



[illegible] Enlarged X-ray pictures of the specimens. Growth of the [illegible] on the right side 6[illegible] per cent and on the left 4[illegible] per cent of the control

Case 21? d (growth 70 per cent of the control) See fig 10 The thickness of the ECP is about the same as in the foregoing case Its form is for the most part relatively regular but it is penetrated by several thin connective tissue bands and one massive partly ossified bridge The thickness of the resting zone varies considerably Except for minor areas of granulation it appears rather amorphous The cartilage columns are short and in the areas of traversing connective tissue bands scatter and diverge from the longitudinal plane A massive partly ossified conical bridge of connective tissue is situated near the border of the ECP The whole plate seems to be inclined to this side and the bony trabeculae in the metaphysis are correspondingly oblique On the opposite side of the metaphysis very intensive bone resorption is seen

Case 212 s (growth ?6 per cent of control) The thickness of the ECP is about the same as that of the control animal The form of most of the plate is more or less regular The resting zone is lacking in many parts its matrix stains unevenly and shows areas of granulation and streaking Numerous deeply staining bands of fibres traverse the ECP In these areas the arrangement of the short palisades of cartilage cells is irregular Near the lateral border of the ECP a partly ossified bridge of connective tissue containing a blood vessel is seen On the proximal surface of the epiphysis a partly ossified piece of cartilage is seen connected to the epiphysis by cartilage tissue

Case 221 d (growth 61 per cent of control) The greater part of the ECP is in some sections relatively regular but very thin The resting zone is lacking in places and in its stead there is a narrow zone of fibrous tissue The columns of cartilage cells are very short consisting of only a few cells The matrix forms massive deeply staining bundles of fibres traversing the whole ECP In some sections connective tissue bands are seen traversing the plate In one section a broad partly ossified bridge of connective tissue is seen and in this area the whole structure of the cartilage is disorganized

Case 221 s (growth 67 per cent of control) In some sections the ECP looks relatively regular especially in its peripheral parts Its structure is very similar to that of the foregoing case with the exception that the matrix is more homogeneous The central part of the ECP is in places very irregular its width varying considerably The resting zone is mostly lacking The columnar arrangement is in many places disordered and the plate is traversed by several partly ossified bridges of connective tissue which contain relatively large blood vessels

Case 2?2 d (growth 68 per cent of control) Compared with the control animal no 82 the ECP is wider Its form and structure are very regular In the resting zone areas of fibrous tissue and unevenly staining areas of matrix are seen In places relatively broad bundles of collagenous fibres traverse the plate The columnar arrangement of the cells is mostly quite regular and the zone of ossification looks normal In one section a bridge of collagenous tissue is seen traversing the plate near its peripheral border In this area a step like formation in the ECP is seen

Case 22? s (growth ?? per cent of control) Only about half of the ECP appears relatively normal In its middle part a massive bridge consisting of bone fibrous tissue blood vessels and scattered cartilage cells connects the epiphysis and the metaphysis The rest of the epiphyseal cartilage consists of unevenly staining areas of cartilage partly separated from each other by fibrous tissue In this area no regular endochondral ossification is seen See fig 10

Case 331 d (growth 9? per cent of control) The microscopic picture corresponds to that of control animal no 7? In its central parts the resting zone shows minor areas of uneven staining and granulation and the zone i in places v w



FIG 11 — ECP graft at the corresponding site in the opposite leg in the dog Above control animal no 3 Below case no 33) d The microscopic structure of the transplanted ECP corresponds to that of the control animal

Case 334 s (growth 67 per cent of control) The histological picture is rather similar to that of the foregoing case except that the resting zone is lacking in places and in the middle of the ECP a narrow band of collagenous tissue traverses the plate

Case 335 d (growth 97 per cent of control) See fig 11 The form and structure of the ECP corresponds to that of control animals nos 73 and 74

Case 335 s (growth 95 per cent of control) No significant difference in the microscopic picture compared with the control animals is observable

The microscopic structure of the ECP was normal in three cases (334 d 335 d and 335 s) The growth of the graft in these was about as great as that of the control In all other specimens microscopic examination revealed changes which were not found in control epiphyseal lines of about the same age Partly or totally ossified bridges of connective tissue were seen traversing the plate in most specimens In some cases the ECP was very irregular and its structure grossly disturbed

TRANSPLANTATION OF THE ECP OF THE FIBULA INTO THE MUSCLE

The results of transplantation of the ECP to the calf muscle both in the rabbit and in the dog are seen in table 6 In the rabbit some growth of the graft was seen in 6 out of 8 experiments In the dog growth had taken place in 3 out of 6 experiments The amount of growth in all of these cases was relatively insignificant The graft was not found in 2 cases in the rabbit and in 3 cases in the dog The diaphyseal end of the graft usually became thin and the radiological density of the graft decreased The graft moved in the distal direction during growth

By measuring the distance between the ECPs of the tibia and the graft an attempt was made to study the possible stimulating effect of the former upon the growth of the graft The results obtained show no definite correlation between the distance and the amount of growth but it is seen that the two best grown grafts were situated very near the ECP of the tibia after transplantation

In fig 12 the development of the graft 233 s which had grown the most is seen

Histological findings

In cases 233 241 and 246 histological examination of the specimens was made

Case 233 s The specimen consists of a piece of bone formed by a peripheral layer of compact bone and a central cancellous layer From the peripheral compact bone trabeculae are orientated towards the centre On one side a layer of hyaline cartilage

TABLE 6 — *Transplantation of the ECP of the fibula into muscle on rabbit (R) and on dog (D)*

Animal No	Age at operation (days)	Time of observation (weeks)	Growth of graft (mm)	Growth of proximal ECP of fibula in control animal (mm)	Growth of proximal ECP of tibia (operated leg) (mm)	Distance of graft from ECP of tibia after operation (mm)	Growth of graft in % of control
R 251 d	19	19	3	31	35 5	7	10
R 251 s	19	19	2 [2])	30	34 5	8	7
R 252 d	19	19	7	30	34	2	23
R 252 s	19	19	2 [2])	29 5	33 5	5	6
R 253 d	19	19	2	29	33	10	6
R 253 s	19	19	9	29 5	33 5	1	27
R 254 d	19	19	0 [1])	32	36	2	0
R 254 s	19	19	0 [1])	32	36	6	0
D 241	23	22	8	49 5	47 5	10	16
D 246	23	22	4 [2])	49 5	48 5	5	8
D 281	16	30	0 [1])	54	52 5	5	0
D 282	16	11	0 [1])	30 5	33 5	19	0
D 283	16	30	0 [1])	54	56 5	10	0
D 284	16	13	3	54	39	4	5

[1]) the graft has been resorbed
[2]) *uncertain because the ECP is not visible*

is seen on the surface of the specimen No signs of endochondral ossification are visible

Case 241 See fig 13 The ECP is relatively regular and wide The epiphysis is partly ossified The resting zone is relatively wide In it blood vessels are seen In many sections the cartilage columns are arranged in a slightly radiating manner The primary spongiosa of the metaphysis looks broader than normal

Case 246 The specimen is composed of a non ossified epiphysis a partial ECP and a metaphysis The ECP only reaches to the middle of the specimen It is very narrow and no regular cartilage columns are seen The cartilage cells are arranged in scattered groups in which the more distally situated cells are oedematous and degenerating The rest of the site of the ECP is filled with fibrous tissue

DISCUSSION

The experiments were performed on both rabbits and dogs which had both advantages and inconveniences The data were less uniform more factors came into play because of the difference in anatomy more technical practice was

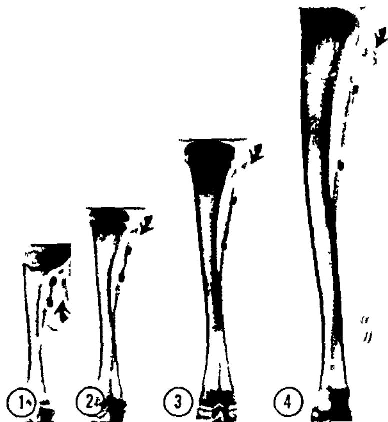


FIG 12 — *Growth of the epiphyseal graft in the calf muscle Rabbit no 253 s The unmarked graft is seen at the site indicated by the arrow X ray picture 6 days (1) 3 weeks (2) 6 weeks (3) and 19 weeks (4) after transplantation In the same leg a suture transplant with markers is seen at the site of the excised fibular ECP*

needed etc Since the earlier experimental investigations have been done almost exclusively on the rabbit this species was chosen as the chief experimental animal for the sake of comparison On the other hand the larger proportions and more human anatomy of the leg of the dog offered a valuable addition to the work Because of the stable anatomical situation and proportionately greater longitudinal growth the ECP of the fibula transplanted to the corresponding site of the opposite leg was suitable for these experiments where the maximal growth capacity was the object of the study The selection of these animals and also of the operative technique and marking procedures took place after a great number of preliminary experiments

The routine X ray methods though quite adequate for checking the growth of the graft were seen to be rather unsatisfactory for a study of the structure of the specimen In this respect the usefulness of the special radiographs was evident

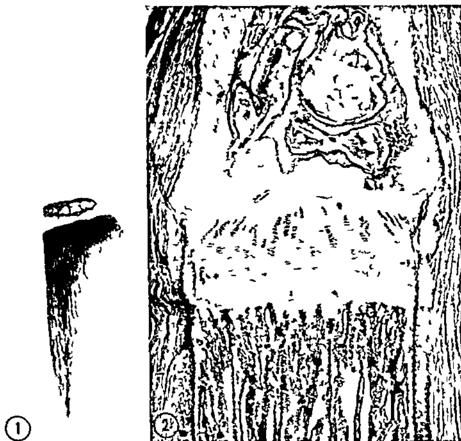


FIG 13 — *Epiphyseal graft in the calf muscle Dog no 241 (1) Enlarged X ray picture of the specimen (2) Microscopic picture of the same The FCP is relatively regular and wide*

In order to reduce any possible error due to using the tibia as a control of the growth two types of control were used In the rabbit the values obtained from the tibia and from the fibula of another animal of the same litter differed significantly It was evident that the graft had disturbed the growth of the tibia in some cases In the dog no difference in the results was noticed This may be because the dog s fibula which is not fused with the tibia did not at least to the same extent have a restraining influence on the growth of the tibia

As was already mentioned the marking method was chosen after many preliminary experiments Many investigators have previously used metal markers but their drawbacks have usually not been pointed out Some authors (*Silfverskiold* 1934 *Bisgaard* and *Bisgaard* 1935 *McElvenny* 1965) have men

tioned them however During growth a continuous remodelling of the bone takes place As the result of growth the marker situated in the metaphysis gradually moves in the direction of the diaphysis As the result of remodelling it may become situated beneath the periosteum The marker situated in the middle of the metaphysis may even become situated in the medullary cavity (*McElhenny*) In the present material it was seen in many cases (see fig 6) that the transverse metal marker often gradually turned in a longitudinal direction and became situated beneath the periosteum

Langenskiold and *Edgren* (1950) noticed that the focal changes caused at the end of the metaphysis by local irradiation gradually moved towards the surface and in the direction of the diaphysis They concluded that in some layer of the ECP a movement of the cells in the transverse direction occurs They also presented the hypothesis that the growth of the periosteum could take place by the same mechanism *Humphry* (1861) was of the opinion that the periosteum grows interstitially If we suppose that the growth of the periosteum is interstitial in contrast to the growth of the bone beneath it the conclusion of *Korneu* (1929) that the tubular bones grow interstitially can perhaps be understood His markings were circular cerclage wires the movement of which would correspond to the growth of the periosteum

In some experiments of the present work the metal marker became situated in the soft tissues outside the bone during growth Then it usually showed a tendency to move distally more rapidly than would be accounted for by growth of the bone This could be clearly seen in instances in which the other marker was situated in the bone This source of error could be eliminated by following the growth radiographically The marker situated beneath the periosteum seemed not to move in respect to the bone

In spite of disagreement among investigators regarding the success of epiphyseal cartilage grafts the experimental results of some authors (*Helferich Heller Fohl Silfverskiold Sousa Pereira Ring Schraiber Heikel*) support the view that preservation of the growth capacity is possible These earlier published investigations did not provide a satisfactory object of comparison for the present work because of the different methods or because exact results and controls were often not given The most satisfactory comparison was offered by the works of *Silfverkskiold* and *Heikel* whose experiments were well planned and so gave very reliable results In the most successful cases transplantation of the ECP to the corresponding site on the opposite leg gave according to *Silfverskiold* growth amounting to 50 per cent of the normal The fibular graft used by *Heikel* when transplanted to the site of the radius in the best cases gave 1/2—2/3 of the growth of the corresponding fibular ECP

In the present work longitudinal growth which was comparable to the normal was seen in some cases in both rabbits and dogs In the light of the results

obtained there should be no doubt that the transplanted ECP can retain its growth capacity and in successful cases grow as much as its origin presupposes A very striking feature was the significant variation in the amount of growth This was reflected rather well in the appearance of the grafts at the end of the observation period Practically all grafts in which growth was clearly disturbed showed macroscopic radiological and microscopic abnormalities A considerable amount of growth was seen in some cases where ossified bridges connected the epiphysis and metaphysis This is in accordance with the results of *Ford* and *Key* (1956) *Sieffert* (1956) *Friedenberg* (1957) and *Johnson* and *Southwick* (1960) who noticed that longitudinal growth could continue in spite of local epiphyseodesis

The result of transplantation to the muscle corresponded to the result obtained by *Heikel* and showed that the graft may continue growing to a slight extent This growth was of no practical value however because the graft became very thin *Silfverskiold* made the same observation in the case of his pedicle graft which grew almost normally in length These results confirm the truth of the statement first made by *Roux* (1895) that preservation of function is essential for successful transplantation The hypothesis that the graft would grow better if its ECP were near the ECP of the neighbouring bone was supported by the two most successful results

What are the factors which cause disturbance or cessation of growth after transplantation? On what does the marked variation in the results depend? The data of the present study permit only a limited discussion of these problems

If the survival of the graft cells is considered essential for the preservation of growth one of the main tasks is the rapid restoration of nutrition The survival of the cells in the germinal layer seems to be especially important Transplantation causes a temporary arrest of nutrition If this interval is too long there is a disturbance or arrest of growth The time needed for revascularization is influenced by the distance that the new vessels have to grow *Stringa* (1957) found the rapidity of revascularization in cortical bone to be 5 mm per week It must be noted however that the vessels of the graft may make contact with the host circulation as soon as the new vessels have perforated them (*Peer* 1955) The periosteum of the autogenous bone graft is revascularized about 24 hours after transplantation (*Hammack* and *Enneking* 1960)

Some earlier investigators (*Heller* 1918 *Silfverskiold* 1934 *Sousa Pereira* 1957 *Ring* 1955) point out that the most successful grafts have been those where the cut line has been near the ECP In the present work the epiphyseal cut line was near the ECP except in those cases where the epiphysis was transplanted as a whole No significant difference in the results was noticed between these two groups No attempt was made to determine the significance of the length of the diaphyseal surface The distance of the cut line from the

ECP was about the same in the same animal species A good initial alignment of the graft in the host area seemed to be of significance for the succesful result

CONCLUSIONS

1 The ECP of the fibula in both the rabbit and the dog may when transplanted to the corresponding site of the opposite leg retain its full growth capacity i e the capacity to be expected in its original site But in spite of great care in technical performance some not easily definable factors very often cause a disturbance of growth

2 In successful cases the transplanted ECP does not differ in either appearance or structure from the normal at the end of the observation period

3 Without bony contact between the graft and the host bone only insignificant growth of the graft can take place

III TRANSPLANTATION OF CRANIAL SUTURE

REVIEW OF THE LITERATURE

The membranous bones of the cranial vault develop in the membranous capsule of the brain from the centres of ossification (*Gardner* 1956 *Weinmann* and *Sicher* 1947) When two adjacent bones come into close relation a suture develops between them which is thus a remnant of the membranous capsule The bone so formed consists of immature coarsely fibrillar bone (*Weinmann* and *Sicher*) also called foetal coarse fibred or plexus like (*Weidenreich* 1950) or primary bone [primares Knochengewabe (*Thoma* 1917–18)] Gradually an outer and an inner layer of compact bone develop on it The formation and remodelling of the particular lamellar structure takes place for the most part postnatally (*Gardner*) As the result of these processes the lamellar structure and the Haversian lamellae of the spongiosa develop By resorptive mechanisms the diploe characteristic of the bones of the cranial vault is formed

The course of the frontal suture is more or less rectilinear on the inner surface of the calvarium on the outer surface it very early becomes serrated Histologically the suture comprises three layers (*Weinmann* and *Sicher*) The middle layer consists of an irregular feltwork of connective tissue fibres It is rich in cells In the middle layer moderate numbers of blood vessels are also seen (*Thoma*) On both sides of the middle layer adjacent to the bone are the peripheral layers which consist of dense connective tissue The fibres of this continue into the bone as Sharpey s fibres The suture is bounded by marginal bone (Agger marginalis *Thoma*) On its margins scattered or in groups osteoblasts are seen which differ very little from the connective tissue cells The osteoblasts near the bone margins are somewhat flattened while those farther from the bone are rounder and more isodiametric At the margins osteoclasts are also situated in the resorption lacunae The marginal bone differs from the other cranial bone in being strongly basophilic and containing an abundance of Sharpey s fibres (*Laitinen* 1956) The affinity for basic dyes decreases with age and in an adult animal there is only a thin dark baso philic layer of bone at the suture margin

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Laitinen (1956) brought about artifical fusion of the sutures in the rabbit by inserting clips into them In some instances the clips served as markers and *showed that the distance between these and the suture increased as a result of* sutural growth

David (1896) reimplanted a piece of the calvarial bone in the dog and followed its fate histologically In the second week vessels grew from the fracture line to the graft The histological picture was normal by the eleventh week He concluded that the major part of the bone survived reimplantation Most investigators have been of the opinion already expressed by *Barth* at the end *of the nineteenth century that all or almost all osteocytes die (Peer 1955)* There is disagreement among authorities regarding the survival of bone cells after transplantation *Peer* in his detailed survey of the literature came to the conclusion that osteocytes in autogenous grafts in favourable transplantation sites survive as living entities especially cancellous grafts with open structure or a thin cortex and in contact with bone

Opinions also differ as to the significance of the periosteum for successful transplantation *Vainio (1948)* in his experimental study on the rabbit came to the conclusion that the periosteum has a vital significance in the regeneration process In his experiments the periosteal graft of compact bone always regenerated more quickly than an otherwise similar graft without periosteum According to *Peer* most investigators now agree that the revascularization of periosteal grafts takes place more quickly but that the periosteum cannot be considered essential for successful transplantation The periosteum like the *fascia graft preserves its structure in transplantation and the connective tissue* cells remain viable (*Peer*)

The poor regenerative capacity of the calvarial bone in the adult human is well known In animal experiments however it has been noticed that repair of calvarial defects readily occurs especially in young animals (*Trott Ky* 1952 *Simpson et al* 1953 *Sirola* 1960) Similarly in children the regenerative capacity of the calvarial bones seems to be much better than in adults (*Glaser* and *Blaine* 1936 *Rowbotham* 1949 *Ingraham* and *Matson* 1954 *Grob* 1957) Relatively large defects of the calvarial bones have been repaired well in infants (*Sirola*) In examining the repair of the defects of calvarial bone in the rabbit and the cat *Sirola* noticed that if the defect was covered with a polythene film the suture did not regenerate even if marked regeneration of the bone took place

The growth of bone grafts embodying the cranial suture seems not to have been the subject of any previous experimental investigation In preliminary *experiments the author (Ryoppy 1961) has made a radiological study of the* reimplanted suture graft and noticed that the suture was able to retain its appearance almost unchanged

PROBLEMS

1. Does the coronary suture preserve its capacity of growth after reimplantation?
2. Does the coronary suture preserve its capacity of growth when it is transplanted as an autograft to the site of the excised LCP of the fibula? What is the extent of its longitudinal growth compared with
   - the growth to be expected in its original site?
   - the normal growth of the corresponding LCP of the fibula?
3. How does the appearance and structure of the sutural graft change in the new site?

MATERIAL AND METHODS

MATERIAL

59 rabbits and 19 mongrel dogs were used as experimental animals. Because of complications 7 rabbits and 2 dogs were excluded from the material. The age of the rabbits varied between 16–40 days and that of the dogs between 16–60 days. The time of observation varied between 11 and 41 weeks. The animals were chosen without reference to sex, size or colour. On animals of the same litter different types of operations were often performed.

The types and number of experiments on both animal groups are listed in table 7. In addition, a number of different control experiments were performed. These are listed in the same table.

OPERATIVE METHODS
(fig. 14)

The anaesthesia and preparation of the animals for operation were the same as in the transplantation of the ECP.

Metal markers in the calvarium. The aim of the experiment was to study how much the coronary suture grows normally and to test the value of the markers as a control method. On each side of the coronary suture at a distance of about 3–5 mm from it, a hole was drilled through the bone with an injection needle and a piece of metal wire 1–2 mm in length was inserted into it.

Reimplantation. The aim of the experiment was to study whether the suture preserves its growth capacity in reimplantation. A longitudinal incision was

TABLE 7 — *Transplantation of calvarial bone graft containing a piece of coronary suture A number of control experiments are included in the table*

Type of experiment		Number of experiments Rabbit	Dog
Transplantation of the suture			
Reimplantation		16	9
Reimplantation with polythene film		6	3
Transplantation to the fibula		32	16
Transplantation to the thigh		8	
		62	28
	Total	90	
Control experiments			
Measurement of normal growth of suture with the aid of metal markers		5	7
Transplantation of calvarial bone to the fibula (without suture)		5	
		10	7
	Total	17	
Total		107	

made on the top of the head The coronary suture was exposed At the site of the suture a rectangular bone plate with its periosteum attached was cut with a scalpel in such a way that the suture ran in the direction of the shorter side of the rectangle The size of the plate in the rabbit was about 6–8 × 4–6 mm and in the dog 9–11 × 7–9 mm The medial incision was some millimetres from the sagittal suture In both short sides of the plate a metal marker was inserted The plate was then reimplanted No fixation was needed Closure was made with interrupted catgut sutures and the wound was covered with a plastic film (Nobecutan®)

Reimplantation with a polythene film The aim was to study whether the suture graft would preserve its growth capacity if it was isolated from the dura The operation was similar to the reimplantation described above except that a circular piece of polythene film cut a little larger than the reimplant was placed in between the bone plate and the dura

Transplantation to the fibula The aim was to study whether the cranial suture transplanted to the site of the excised ECP of the fibula would preserve its growth capacity The bone plate containing the coronary suture was taken and marked as described above The graft was placed in physiological saline

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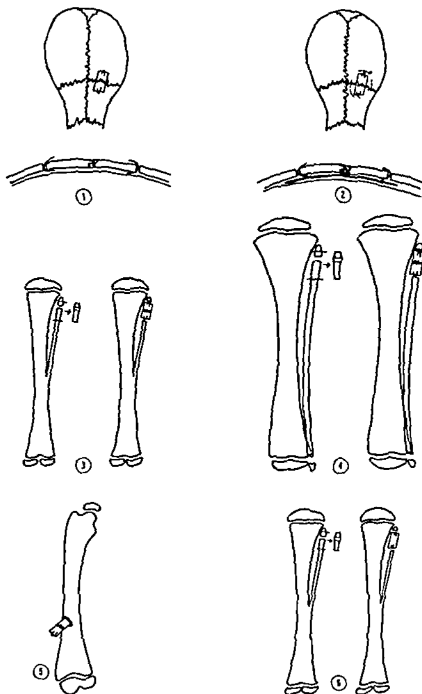


FIG 14 — Transplantation of the cranial suture Operative methods (1) Reimplantation of the bone plate containing a piece of coronary suture (2) Reimplantation with polythene film placed in between the graft and the dura (3) Transplantation of suture graft t the site of the excised ECP of the fibula in the rabbit (4) The same in the dog (5) Transplantation into the thigh (6) Transplantation of a piece of parietal bone to the site of the excised ECP of the fibula (control experiment)

solution A piece of bone containing the ECP and part of the epiphysis and metaphysis was resected from the upper end of the fibula by the method described in the transplantation of the ECP The length of the piece was measured before cutting and the defect made as long as the suture graft The sutural graft was placed in the defect in the fibula No fixation was used in most cases In some instances the graft was fixed in the diaphysis by inserting a short piece of metal in between the graft and the medullary canal

Transplantation into the thigh The aim of the experiment was to study whether the suture graft placed as a branch to the diaphysis of the femur would preserve its growth capacity One of the short sides of a suture graft of the same type as above was inserted into a hole made in the cortex in the middle third of the femur The direction of the graft was at an acute angle distally Fixation was effected by suturing the muscles over the graft

Transplantation of calvarial bone of the fibula (without the suture) The aim was to see whether the distance between the metal markers at the ends of the bone plate would remain unchanged if no growth was to be expected A bone plate of the same size as the suture graft above was removed from the parietal bone and transplanted to the site of the excised ECP of the fibula

CONTROL METHODS

Reimplantation The control methods for the rabbit and the dog were different

R a b b i t The sagittal length of the cranial vault was measured in a number of rabbits of different ages For the measurements lateral view radiographs were used The anterior point of measurement was the ridge in the frontal bone in the middle cranial fossa and the posterior point was the posterior margin of the parietal bone in the cranial fossa The curve drawn from these readings (see results fig 15 p 64) was used as the control of the growth of the coronary suture

D o g The increase in length of the calvarium was used as the control of the growth of the coronary suture Because of differences in anatomy (*Sisson* and *Grossman* 1945) the method of measurement was a little different from that used on the rabbit The measurement was made from the anterior margin of the middle cranial fossa to the posterior point of the posterior cranial fossa

Because of the great variation in the size of the mongrel dogs a control method of the type used for the rabbit was considered unsatisfactory Instead another dog of the same litter was used as the control animal This also had the disadvantage that in some cases the difference in size became disturbingly great In these cases the length of the calvarium of the experimental animal

was considered a more reliable control To get the relation between the increase in the length of the calvarium measured by this method and the growth of the coronary suture control experiments were made in which the metal markers were inserted on both sides of the coronary suture (see results table 8 p 63)

Transplantation to the fibula

R a b b i t The controls for the sutural growth were made by the same method as in the reimplantation As controls of the growth of the ECP of the fibula both the opposite fibula and that of another animal of the same litter were used The cases in which the latter method was used are mentioned separately in the results To enable the evaluation of the error of the latter method the growth of the proximal ECP of the tibia was also measured

D o g The growth in length of the calvarium of the same animal measured and corrected as above was used as the control The defect was assumed not to disturb the growth of the calvarium markedly The control experiments *regarding the growth of the fibular ECP were made by the same method as in* the rabbit

Transplantation to the thigh The method of control of sutural growth was the same as described above for the rabbit

RADIOLOGICAL AND HISTOLOGICAL METHODS

As a control of the growth of the suture reimplant a lateral view radiograph was used The X ray picture of the specimen was made by placing the cranial vault cut off after sacrifice of the animal on the film For histological examination the specimen was cut in the sagittal plane

RESULTS

NORMAL GROWTH OF THE CORONARY SUTURE

The results of the measurement of the growth of the coronary suture measured by the insertion of metallic markers on both sides of the suture are seen in table 8 The variation of the increase in the distance between the markers is considerable in both the rabbit and the dog This is probably due to expelling of the markers as the result of remodelling of the bone Therefore this method could not be accepted as providing a satisfactory control of sutural growth without further study When the increase in the distance between the markers was compared with the average growth in length of the calvarium it could be seen that in the rabbit the greatest increase corresponds to the growth

in length of the calvarium i e the difference is within the error of measure ment 0 5 mm Therefore in the rabbit the growth in length of the calvarium measured by this method was considered to be a satisfactory control without correction

In the dog the increase in the distance between the markers did not correspond to the growth in length of the calvarium Supposing that the greatest increase 2 5 mm corresponds to the growth of the suture the correction of the readings obtained from the growth in the length of the calvarium was obtained by multiplying it by 2 5/5 5 This corresponds to the growth of the coronary suture

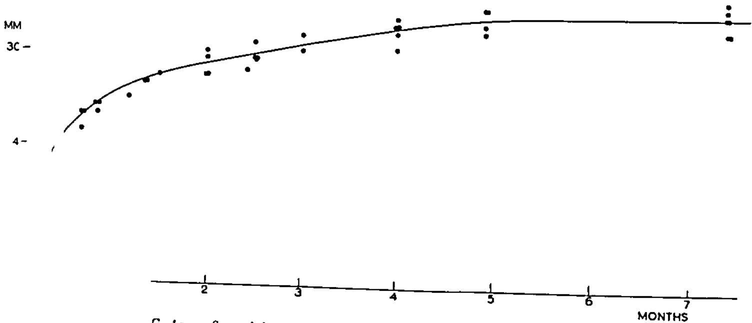
The curve in fig 15 shows the length of the calvarium of the rabbit at different ages measured on a number of normal animals The readings in this curve were used as the control values for sutural growth in the rabbit

TABLE 8 — *The growth of the coronary suture measured as the increase in the distance between metal markers on either side of the suture R=rabbit D=dog*

Animal No	Age at operation (days)	Time of observation (weeks)	Distance between markers (mm) Initial	Final	Increase	Average growth in length of calvarium in control group (mm)	Growth in length of calvarium (mm)
R 301	16	41	5	11	6	-	
R 302	16	41	7	13 5	6 5	-	
R 304	16	41	7 5	10	2 5[1])	7	
R 305	16	41	6 5	8 5	2)	7	
R 306	16	41	6 5	11	4 5[1])	7	
D 71	41	17	10	12 5	2 5		5 5
D 72	41	17	11 5	13 5	2 5		5 5
D 73	41	17	10 5	11 5	1[1])		6 5
D 74	41	17	9 5	11 5	2		5
D 81	44	14	10 5	12	1 5		6.5
D 82	44	14	10	?	?[1])		5 5
D 83	44	14	9 5	10	0 5[1])		7

[1]) one marker expelled

) both markers expelled



G 1ɔ — *Sagittal length of the calιarιum of the ral l ıt at different ages The measurements u ere made on a group of control animals*

REIMPLANTATION OF THE CORONARY SUTURE ON RABBIT

The results of reimplantation of the coronary suture in the rabbit are seen in table 9 *In 10 of the experiments growth of the reimplant was noticed. The* amount of growth was comparable to normal in three cases In the most successful experiments both the radiological appearance of the suture and the radiological density of the graft were normal as interpreted from the X ray pictures of the specimens Bone defects usually minor ones were seen at the borders of most grafts but these did not seem to have disturbed the growth In fig 16 two examples of the specimens are seen

TABLE 9 — *Reimplantation of the coronary suture in the rabbit*

Animal No	Age at operation (days)	Time of observation (weeks)	Growth of graft (mm)	Growth of coronary suture in control group (mm)	Growth in % of control	Macroscopical and radiological observations		
						Suture	Bone defects	Radiol density of bone
20	40	7	0	2.5	0	fused	present	normal
21	40	7	0	2.5	0	partially fused	present	uneven
22	40	7	2	2.5	80	patent	present	normal
23	40	7	2.5	2.5	100	patent	absent	normal
24	40	7	2.5	2.5	100	patent	present	normal
25	40	7	0	2.5	0	fused	absent	uneven
26	40	7	3	2.5	120	patent	present	normal
27	30	6	0	3	0	fused	present	uneven
28	30	6	2	3	67	patent	absent	uneven
29	30	6	0.5	3	17	partially fused	absent	uneven
30	30	6	2	3	67	partially fused	present	normal
31	30	6	0	3	0	partially fused	present	uneven
32	30	6	1.5	3	50	partially fused	present	normal
33	30	6	1.5	3	50	partially fused	present	normal
65	19	24	3	6.5	46	fused	present	normal
66	19	24	3.5	6.5	54	patent	absent	uneven



FIG 16 — Suture reimplant in the skull of the rabbit Two examples of the X ray pictures of the specimens Left case no 23 Right case no 21 The metal markers were used for the measurement of growth Note the bone defect in case no 21

Histological findings

In cases 25 (reimplant and control) 26 (reimplant and control) 327 (control) 24 25 28 30 32 and 35 histological examination was made

Case 23 (control age 13 weeks) The suture appears as an S shaped relatively broad structure composed of collagenous tissue The thickness of the specimen in this section is about 2/3 mm and the breadth of the suture about 1 1/2 mm The suture is relatively rich in cells and the feltwork of connective tissue fibres appears fairly homogeneous The fibres are seen continuing to the marginal bone which is strongly basophilic In places osteoblasts are seen in abundance at the bone margins The marginal bone forms long trabeculae which are responsible for the S shaped form of the suture Some osteoclasts are seen at the bone margins In places slight granulation of the collagen fibres is seen The diploe and the tables are well formed

Case 26 (control age 15 weeks) The suture is somewhat more massive and tortuous than in the foregoing case but its microscopic structure is otherwise similar

Case 327 (control age 52 weeks) See fig 17 The thickness of the specimen at the site of the suture is about 1 mm and the length of the area of the suture about 2/5 mm The course of the suture is not so clear cut as in the two foregoing cases The suture is in places interrupted by narrow zones where the edges of marginal bone are almost



FIG 17 — *Microscopic structu e of the normal coronary suture of the ral bit at the age of 32 u eeks Case no 3.7 Belou the structure of the suture at higher magnification The sutu e shoi s areas of fatty degenerati in Note the osteoblast cells lining the sutu e*

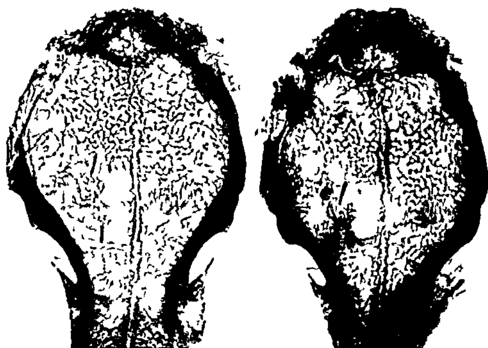


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TABLE 10 — *Reimplantation of the coronary suture in the dog*

Animal No	Age at operation (days)	Time of observation (weeks)	Growth of graft (mm)	Growth in length of calvarium (mm)	Calcul growth of coronary suture (mm)	Growth in % of control	Macroscopical and radiological observations		
							Suture	Bone defects	Radiol density of bone
4	41	22	1 5	5	2 5	60	patent	absent	normal
83	45	14	0 5	7	5	17	fused	absent	increased in suture area
241	25	22	6	11	5	120	patent	absent	increased at suture margins
246	23	22	6	11 5	5	120	patent	absent	normal
281	16	30	6	15	6	100	patent	absent	uneven
282	16	12	5	11 5	5	100	patent	absent	uneven
283	16	30	5	13	6	85	fused	absent	uneven
284	16	30	6	12 5	5 5	109	patent	absent	increased at suture margins

coronary suture at the site of reimplantation was mostly very narrow or ossified In most cases the other parts of the coronary suture were also already closed except in the area immediately adjacent to the sagittal suture No bone defects were seen at the borders of the graft The radiological density on both sides of the suture was increased in 3 cases

In figures 16 and 17 two examples of reimplantation of the suture in the dog are seen

Histological findings

In cases 82 (control) 75 (control) 331 (control) 74 83 283 and 284 histological examination was made

Case 82 (control age 19 weeks) The thickness of the specimen at the site of the suture is 3 mm and the length of the suture area about 6 mm The course of the suture across the bone is oblique The suture runs a slightly tortuous course Its thickness varies considerably being greatest in the middle and least near the periosteum and the dura The greater part of the suture is rich in cells especially the middle layer Abundant osteoblasts are seen arranged in rows at the bone margins Osteoclasts are also seen in resorption lacunae The collagenous fibres appear regular The marginal bone is strongly basophilic and mostly coarse-fibred A relatively massive layer of bone separate the suture from the diploe The outer plate is considerably thicker than the inner one



FIG 18 — Growth of the reimplanted coronary suture graft in the dog Case no 246 X ray pictures 2 days (1) 2 weeks (2) 7 weeks (3) and 15 weeks (4) after reimplantation Note the gradual increase in the distance between the markers

Case 73 (control age 26 weeks) The course of the suture is not so oblique as in the foregoing case The suture cells are less numerous and the layer of coarse fibrillar bone on the two sides of the suture is narrower The suture is thinner in the middle than in the peripheral parts Signs of degeneration are seen in the connective tissue The outer plate is very thick compared with the inner one

Case 331 (control age 32 weeks) See fig 20 The course of the suture is very oblique It is only very gently sinuous The thickness of the suture varies little but it is slightly thinner on the periosteal side The suture is mostly relatively poor in cell Osteoblasts are seen in moderate numbers but in the marginal bone only small remnants of coarsely fibrillar bone are seen and the staining of the marginal bone does not differ much from that of the rest of the bone No bony bridges traversing the suture are seen



FIG 19 — *Coronary suture re mplant in the dog Specimen of case no 4 On the control side (at the left of the picture) sho t straight pieces of metal markers are placed on both sides of the suture for measurement of sutural grou th The coronary suture is seen as a very narrou line*

Case 74 (growth 60 per cent of control) The thickness of the specimen at the site of the suture is 4 mm The length of the suture area is 5 mm The suture is mostly of about the same thickness as in case 75 but in some sections there are areas in which the bone edges are almost in contact with each other Near the outer surface the number of connective tissue cells is less than in the middle and inner parts where areas with abundant cells are seen Here numerous osteoblasts are also situated at the bone margins In places osteoclasts are seen The suture tissue shows marked changes of fatty degenerat on especially in its outer parts A coarsely fibrillar type of bone is seen as a thin layer in the middle and inner parts of the specimen The outer table is very massive

Case 83 (growth 17 per cent of control) At the site of the suture a narrow oblique band of connective tis ue is seen This is interrupted in many places by transverse bony bridges In the suture tissue there are only a few scattered cells and no osteo blasts The marginal bone is lamellar in structure and its staining capacity is the same as that of the more remote bone

Case 283 (growth 85 per cent of control) The suture forms an oblique mostly very narrow gently sinuous structure which in places is traversed by bony bridges There are scanty cells and only in places are osteoblasts and coarsely fibrillar bone visible The structure of the collagenous tissue hows considerable changes of fatty degeneration and granulation

Case 284 (growth 109 per cent of control) The outer and middle parts of the suture is very oblique gently winding and thin in places almost indistinguishable and very poor in cells A narro layer of coarsely fibrillar b ne is seen on both sides of it The inner part of the suture is in some sections relatively ide and rich in cells Osteoblasts are se at the bone margins and the marginal bone consists of a relatively wide layer of bas philic coarse-fibred bone

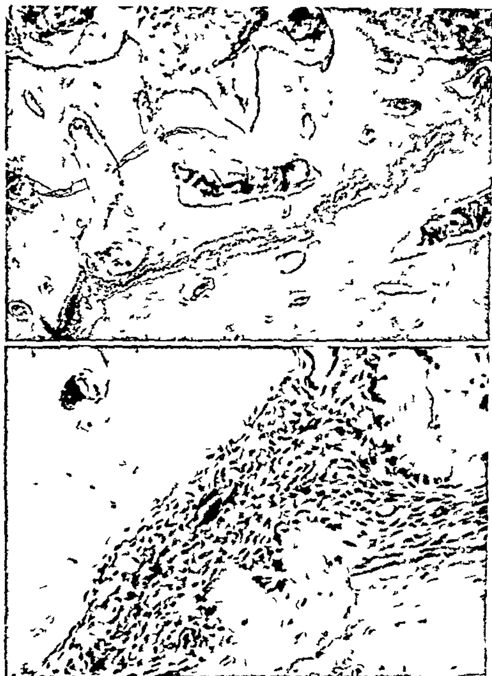


FIG 20 — *Microscopic structure of the normal coronary suture of the dog at the age of 32 weeks Case no 331 Above the course of the suture is only very gently sinuous Below a higher magnification of the suture A narrow one of coarse fibred bone is seen at the sutu e margins*

The microscopic picture of the suture in case 284 did not differ significantly from that of the normal suture at the same age. In all other specimens signs pointing to a decreased proliferative activity compared to the controls were seen.

REIMPLANTATION OF THE CORONARY SUTURE WITH POLYTHENE FILM

The results of reimplantation with polythene film in both the rabbit and the dog are seen in table 11.

TABLE 11. — *Reimplantation of the coronary suture with polythene film in the rabbit (R) and the dog (D)*

Animal No	Age at operation (days)	Time of observation (weeks)	Distance between markers (mm) Initial	Final	Increase	Growth of control (mm)	Growth of graft in % of control
R 151	21	22	6	6	0	6	0
R 152	21	22	5	5	0	6	0
R 153	21	22	6	6	0	6	0
R 154	21	22	6	6	0	6	0
R 155	21	6	6.5	6	−0.5	3	0
R 156	21	22	5.5	6	0.5	6	0
D 331	26	27	9.5	14	4.5	6.5	69
D 332	26	27	8	16	8	7	114
D 333	26	27	8.5	12.5	4	6	67

In *the rabbit* no increase in the distance between the markers was noticed in any of the experiments. Bone was formed on the dural side in all cases and thus the piece of polythene was inclosed inside the bone. The new bone was removed before radiography but the suture was only visible in case *153*. Even in this it was very narrow and the radiological density on either side of it was increased. The radiological density at the site of the suture was uneven in all cases. In case *154* a tiny bone defect was seen on the dorsomedial border of the graft.

In *the dog* the distance between the markers had increased in all 3 experiments. The polythene film was covered with a layer of bone on the dural side. In case *332* a narrow open suture was seen. On both sides of it the radiological density was increased.

Histological findings

In cases 153 331 and 332 microscopic examination was made
Case 153 The suture is partly ossified and partly consists of a narrow band of fibrous tissue with few cells The matrix shows pronounced degenerative changes No osteogenesis is seen The marginal bone is lamellar and the borderline between the suture and the marginal bone is very sharp
Case 331 The course of the suture is oblique running rather straight through the bone It is relatively poor in cells hardly any osteoblasts are visible The matrix shows slight granulation in places No coarse fibrillar bone is seen in the marginal bone
Case 332 The suture is a relatively wide meandering structure also including some isolated islets of connective tissue It is rich in cells and the matrix appears homogeneous Minor blood vessels are seen in the central layer In places relatively abundant osteoblasts are situated in rows at the bone margins Most of the marginal bone i coarsely fibrillar in structure

TRANSPLANTATION OF THE SUTURE TO THE FIBULA IN THE RABBIT

The results of transplantation to the fibula are seen in table 12 In 22 of the 29 experiments growth was demonstrable In 5 cases the amount of growth was practically as great as that of the ECP of the fibula When the growth of the graft was compared with that of the corresponding coronary suture in the calvarium it was noticed that in 20 cases it had grown as much as or more than the latter and in some experiments about 5 times as much In the most successful experiments the suture at the site of the graft had remained open radiologically the graft had fused to the diaphysis of the fibula and its radiological density was interpreted as normal The initial aligment of the graft in the host area was good in all cases where the transplant had grown well In some experiments the result was poor in spite of good initial alignment In some cases the first X ray check up revealed bowing of the graft at the site of the suture or fracture of the fibula distally of the graft In 5 cases the site of the markers made the amount of growth measured uncertain The *fusion to the epiphysis* did not seem to affect the result In 3 cases a bony bridge had formed between the graft and the diaphysis of the tibia The form of the graft changed considerably during the time of observation The thin plate gradually became a massive shuttle shaped bone in the middle of which the suture was seen as a kind of transverse junction of irregular form The radiological structure of the bone in the specimens had a special character The arrangement of the bone trabeculae somewhat resembled that of the cranial bone but the trabeculae were arranged more longitudinally than in the latter and no signs of the diploe were seen

In figures 21 and 22 two examples of the experiments arc seen

In figure 23 a graphical illustration of the growth of the grafts compared both with the growth of the normal suture and with that of the ECP of the fibula is presented

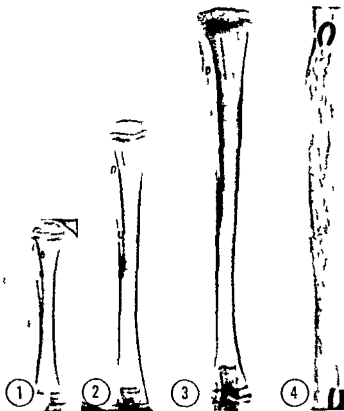


FIG 21 — *Transplantation of the cranial suture to the site of the excised fibular ECP Rabbit no 1 6 X ray picture 6 days (1) 9 weeks (2) and 19 weeks (3) after transplantation Note the gradual increase in the distance between the markers (4) Enlarged X ray picture of the specimen In the middle of it the suture is seen a a light area*

Histological findings

Ca es 114 171 172 1/5 1"4 175 1"6 25? d 25? s 255 d 502 501 and 52/ were examined microscopically

Case 114 (growth 8 per cent of control epiphyseal growth) The thickness of th pecimen is 4 mm and the length of the suture area is also 4 mm The suture forms a very to tu s fibrous structure in which the bone spicules of the marginal bone are situat d in bet ween the bends and bony islets are included in the suture tissue The conn t ve tissue is relatively poor in cells and shows considerable degenerative change O teobla ts are seen abundantly in some of the margins of the bony trabe

TABLE 12 — *Transplantation of the suture to the site of the excised ECP of the*

Animal No	Age at operation (days)	Time of observation (weeks)	Growth of *graft* (mm)	Growth of coronary *suture* in control group (mm)	*Growth in % of sutural growth*	Growth of proximal ECP of tibia (mm)	Growth of ECP of control fibula (mm)	*Growth in % of epiphyseal growth*
112	22	22	0 5	6	*8*	26 5	23 5	*2*
114	22	22	3 5	6	*58*	26	27	*8*
171	28	19	0	5	*0*	26	26	*0*
172	28	19	20	5	*400*	24	28 5	*71*
173	28	19	28	5	*560*	27	23 5	*119*
174	28	19	0	5	*0*	28 5	25	*0*
175	28	19	0	5	*0*	30.5	26 5	*0*
176	28	19	24 5	5	*490*	25	21 5	*114*
251 d	19	19	5 5	6	*92*	35 5	32 5	*17*
251 s	19	19	5 5	6	*92*	34.5	32 5	*15*
252 d	*19*	*19*	*8 5*	*6*	*142*	34	32 5	*26*
252 s	19	19	12 5	6	*240*	33 5	32 5	*38*
253 d	19	19	29 5	6	*492*	33	32 5	*91*
253 s	19	19	14 5	6	*241*	33 5	32 5	*45*
254 d	19	19	24	6	*400*	36	32 5	*74*
254 s	19	19	1 5	6	*25*	36	32 5	*5*
301	16	43	10	6 5	*154*	40	33 5	*30*
302	16	43	6 5	6 5	*100*	39	35	*19*
304	*16*	45	24 5	*6 5*	*377*	42 5	*37*	*66*
305	16	45	7	6 5	*108*	38	33 5	*21*
306	16	45	8 5	6 5	*131*	44	35	*24*
311 [1]	37	25	0	4	*0*	22 5	22	*0*
312 [1]	37	25	0	4	*0*	19 5	20	*0*
313 [1]	37	25	0	4	*0*	11	24	*0*
325	22	30	6 5	6	*108*	27 5	23 5	*28*
326	22	30	6 5	6	*108*	29 5	28	*23*
327	22	30	26 5	6	*442*	33 5	30 5	*87*
328	22	30	19 5	6	*325*	24	20 5	*95*
329	22	30	26	6	*433*	24	28	*93*

another animal of the same litter

[1] the initial length of the graft 18—19 mm i e about three times as much as in the standard grafts

fibula in the rabbit

Macroscopical and radiological observations					
Suture	Fusion of graft to epiphysis	Fusion of graft to diaphysis	Radiol density of bone	Initial alignment of graft	Special observations
not visible	fused	not fused	uneven	poor	f act e f b l b th m ke s e pelled
not visible	not fused	fused	increased	unsatisf	f t f b l g fr f d s de to s d w th t b a
not visible	not fused	not fused	decreased	poor	
patent	fused	fused	normal	satisf	
patent	fused	fused	normal	good	
patent	fused	fused	uneven	satisf	t e-l k form t d stally from d stal m k
not visible	not fused	fused	increased	poor	g ft b k t the t e
patent	fused	fused	normal	good	
narrow	not fused	not fused	decreased	poor	f acture l f b la
not visible	not fused	not fused	decreased	unsatisf	
not visible	fused	not fused	decreased	satisf	
narrow	fused	fused	decreased	satisf	d stal m k at s t e
patent	not fused	fused	decreased	good	the spec me s ve y thin
patent	not fused	fused	decreased	good	
patent	not fused	fused	normal	good	bo b dg b tw f b l d t b
patent	not fused	fused	increased	satisf	f tu f b l p o m t m k t t
patent	fused	fused	normal	unsatisf	d t l m k pell d
narrow	not fused	narrow bridge	normal	unsatisf	bow g at s t aft t spl t t on
patent	not fused	fused	normal	poor	bone b dge b tw g aft d t b
partly fused	not fused	not fused	normal	poor	
not visible	not fused	not fused	decreased	good	
not visible	)	not fused	normal	poor	
not visible	)	fused	increased	unsatisf	m ked b w g f t b
not visible	)	fused	increased	satisf	m ked b w g of t b bon b dg betwe g ft d t b
not visible	fused	not fused	normal	good	
not visible	fused	fused	increased	satisf	sl ght bow g f t b a
patent	not fused	fused	normal	good	
patent	fused	fused	normal	good	
patent	not fused	fused	normal	good	

) the epiphysis totally removed fusion of the graft to the metaphysis of the tibia

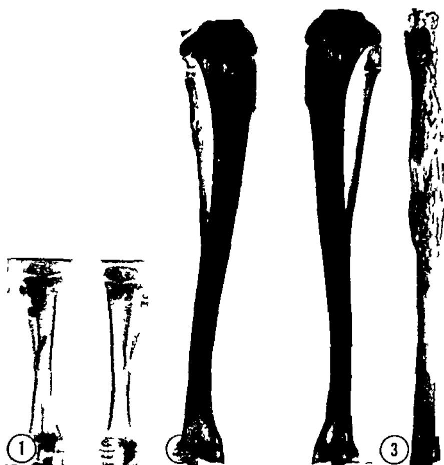


FIG 22 – *Suture transplant at the site of the excised ECP of the fibula in the rabbit Case no 32/ (1) X ray picture after transplantation (2) The specimen The left side was used as a control The growth of the graft was 87 per cent of that of the fibular ECP (3) Enlarged X ray picture of the specimen Note the suture in the middle of the graft*

culae In others the number of osteoclast cells in the resorption lacunae is consider able Only small areas of coarse fibred bone are een The diploic cavities on both sides of the suture are very wide The bone of the specimen is cancellous

Case 1/1 (growth 0) The pecimen is very osteoporotic In the middle of it some thin streaks of fibrous tissue at places interrupted by bony bridges are seen traversing the bone These ontain very few cells and collagen fibres No signs of osteogenesis are visible

Case 1 2 (growth 71 per cent) The thickness of the specimen is 3 mm and the suture area is 7 mm in length Throughout its length the suture consists of bends in between

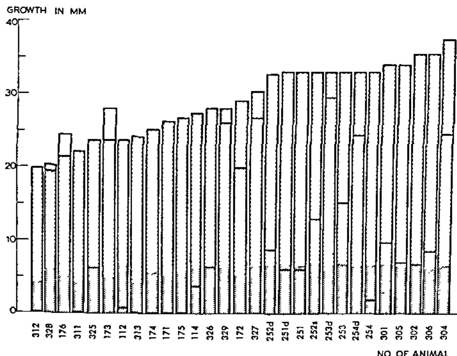


FIG 25 — *Transplantation of the coronary suture to the site of the excised ECP of the fibula in the rabbit The growth of the grafts (level of the transverse lines) as compared with the normal growth of the suture (dark columns) and with that of the fibular ECP (hatched columns) In two cases the graft had grown more than the ECP control*

which long narrow bony islets are situated The suture tissue is rich in cells and collagen fibres which are seen to continue into the bony trabeculae as Sharpey s fibres The fibroblasts in the peripheral layer of the suture have a round and rather large nucleus At the margins of the trabeculae abundant osteoblasts are seen arranged in rows Over large areas apposition of coarse-fibred bone on the trabeculae is seen to have occurred The bone of the specimen is cancellous and the cavities on both sides of the suture are rather wide and numerous No tables or cortical layers of bone are seen

Case 173 (growth 119 per cent) The specimen consists of a piece of bone with a defective epiphysis at one end This has fused to the graft No signs of an ECP are visible At a distance of about 15 mm from the epiphysis a suture is seen the structure of which is very similar to that of the foregoing case In between the epiphysis and the suture the structure of the bone resembles that of a normal diaphysis of the fibula

Case 174 (growth 0) In the area between the marks no signs of the suture are visible The bone is rather osteoporotic At a distance of 20 mm from the proximal end of the specimen a relatively massive suture like structure is found where a rather intensive process of ossification is seen

TRANSPLANTATION OF THE SUTURE TO THE FIBULA IN THE DOG

The results of the transplantation of the suture to the site of the excised ECP of the fibula in the dog are seen in table 13. An amount of growth which exceeded the error of measurement was seen in all 14 experiments. In case 81 it was quite insignificant and in case *283 d* the result was uncertain because the marker had been expelled. In 5 experiments the growth was more than 50 per cent of that of the corresponding ECP of the fibula, in the two most successful cases about 75 per cent of it. Compared with the normal growth of the coronary suture in the skull it was even 6—7 times as great. At the end of the observation time the suture was radiologically open in most cases. The fusion of the graft with the epiphysis seemed to bear no relation to the result. Fusion

TABLE 13 — *Transplantation of the suture to the site of the excised proximal ECP*

Animal No	Age at operation (days)	Time of observation (weeks)	Growth of *graft* (mm)	Calcul growth of coronary *suture* (mm)	*Growth in % of sutural growth*	Growth of proximal ECP of tibia (mm)	Growth of proximal ECP of control fibula (mm)	*Growth in % of epiphyseal growth*
71	41	22	20.5	3	*683*	27	26.5	*77*
72	41	22	20.5	3.5	*585*	29.5	28	*73*
73	41	22	16.5	3	*550*	36.5	37.5	*44*
81	45	15	1	3.5	*29*	17	19	*5*
82	45	15	13.5	2.5	*540*	19	24	*56*
241	23	22	28.5	5	*570*	47.5	49.5	*58*
246	25	22	30.5	4.5	*677*	48.5	49.5	*62*
281 d	16	30	26	6	*433*	52.5	54	*48*
281 s	16	30	23	6	*383*	54.5	54	*43*
282 d	16	13	14.5	5	*290*	35.5	30.5	*48*
282 s	16	15	13.5	5	*270*	33.5	30.5	*44*
283 d	16	30	6.5¹)	6	*(108)*	56.5	54	*(12)*
283 s	16	30	18	6	*300*	54	54	*33*
284 d	16	30	21	5.5	*382*	39	54	*39*
284 s	16	30	19	5.5	*345*	44	54	*35*

another animal of the same litter
¹) the marker expelled

to the diaphysis of the fibula had taken place and the radiological density was interpreted as normal in almost all cases The initial alignment of the graft in the host area was good in most experiments The unsatisfactory position of the markers made the result uncertain in 2 cases The transplant originally a flattish plate had been transformed to a shuttle shaped and in many cases very massive piece of bone There was some variation in the final form of the grafts The structure of the bone differed from that of either the cranial bone or the fibula The bone of the specimen consisted of cancellous bone where the criss crossing trabeculae were rather longitudinal The form of the suture in the specimens varied significantly

Some examples of the growth of the transplants and of the radiological appearance of the specimens are seen in figures 25 and 26

of the fibula in the dog

Macroscopical and radiological observations					
Suture	Fusion of graft to epiphysis	Fusion of graft to diaphysis	Radiol density of bone	Initial alignment of graft	Special observations
patent	not fused (f sed to f b a)	fused	normal	good	t ry obl qu
patent	fused	fused	normal	good	
patent	not fused (f sed f f b)	fused	increased	good	d t l m ker t the tu e
not visible	fused	fused	normal	unsatisf	d fect f b l too long
patent	fused	fused	normal	good	
patent	fused	fused	normal	good	
patent	fused	fused	normal	good	
patent	fused	fused	normal	good	
patent	fused	fused	normal	good	
patent	not fused	fused	normal	good	
patent	fused	fused	normal	good	
patent	not fused (f ed f f b)	fused (w th g l t o)	increased	satisf	g ft b wed at s t p m l ma k t tu e
patent	not fused	fused	normal	good	
patent	fused	fused	normal	unsatisf	g ft bow d fter tr pla t t on
patent	fused	fused	normal	good	

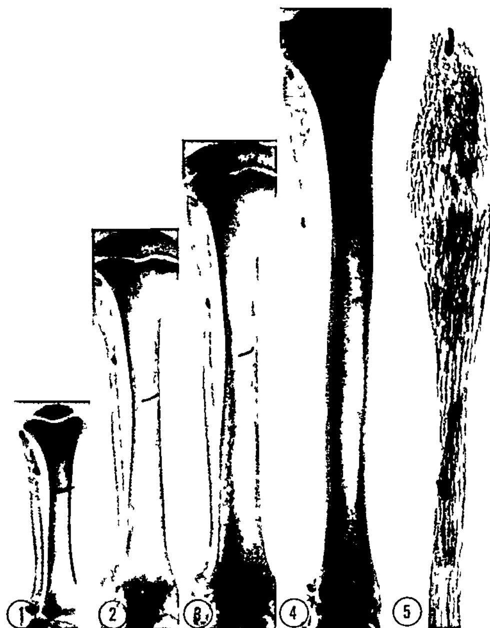


FIG 25 — *Growth of the suture graft in the site of the excised proximal ECP of the fibula in the dog Case no 241 X ray picture 2 weeks (1) 7 weeks (2) 11 weeks (3) and 22 weeks (4) after transplantation Note the gradual increase in the distance between the markers (5) Enlarged X ray picture of the specimen Note the form of the graft and of the suture*

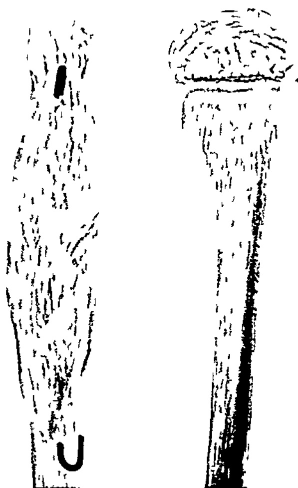


FIG 26 — *Coronary suture graft at the site of the excised ECP of the fibula Dog no 82 Enlarged X ray picture of the specimen (left) and the control fibula (right)*

In figure 27 a graphical illustration of the growth of the suture transplants in the dog compared with the growth of both a normal coronary suture and that of the ECP of the fibula is presented

Histological findings

Cases 71 81 82 211 216 281 d 281 s 283 d 284 d and 284 s were examined microscopically

Case 71 (growth 77 per cent of control epiphyseal growth) The thickness of the specimen is 4 mm and the suture area is 4 mm in length The suture forms a complex

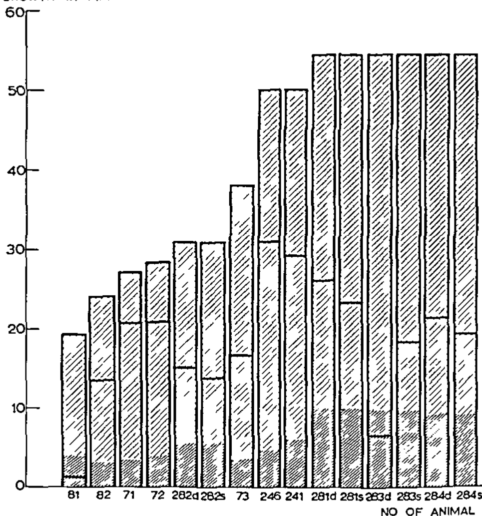


FIG 27 — *Transplantation of the coronary suture to the site of the excised ECP of the fibula in the dog The growth of the grafts (level of the transverse lines) as compared with the normal growth of the suture (dark columns) and with that of the fibular ECP (hatched columns)*

structure in which the broad meanderings enclose relatively elongated bony islets and are separated from each other by the bone spicules of the marginal bone The connective tissue is relatively rich in cells but the matrix shows marked degenerative changes Osteoblasts are seen in abundance but the blood vessels are relatively few A rather broad area of the marginal bone is coarsely fibrillar In places numerous osteoclasts are seen in resorption lacunae both at the suture margins and on the outer and inner margins of the bone The bone is cancellous no tables or diploe are to be seen

Case 81 (growth ɔ per cent) No signs of the suture are found The specimen consists of cancellous bone at the end of which a layer of hyaline cartilage is visible

Case 82 (growth 56 per cent) The suture is a complex massive winding structure 6 mm in breadth There are cells and fibres in abundance Wide spread degenerative changes are seen in the connective tissue The central part of the larger areas of suture tissue are ossified Moderate blood vessels are seen in the central layer The marginal bone is mostly coarse-fibred

Case 241 (growth 58 per cent) The thickness of the specimen is 7 mm The suture is a very massive winding structure 5 mm in breadth The thickness of the streaks of of connective tissue varies a lot being very great in places The cells and fibres are abundant, and the degenerative changes not so marked as in the foregoing case The cells in the peripheral layers are very large and round and osteoblasts are abundant The marginal bone is coarse-fibred The bone is cancellous lamellar See fig 28

Case 246 (growth 62 per cent) In form and structure the suture does not differ significantly from that in the preceding case At the top of the specimen a partly ossified epiphysis is seen fused with the graft

Case 281 d (growth 48 per cent) The suture with its bends running almost longitudinally across the section is 6 mm in breadth The thickness of the separate streaks varies considerably In some places they are almost indistinguishable in others very broad and rich in cells Osteoblasts are relatively abundant The marginal bone is formed mostly by a narrow area of coarse fibred bone

Case 281 s (growth 45 per cent) No significant difference from the foregoing cases is seen in the histological picture The marginal bone is in places lamellar up to the suture

Case 283 d (growth 12 per cent) Across about half the thickness of the specimen a thin complex winding suture is seen Over the rest all that is visible are scattered remnants of the suture separated from each other by bone

Case 284 d (growth 59 per cent) The suture forms a winding structure mostly of thin streaks of connective tissue across an area 8 mm in breadth The lamellar bone between the streaks shows an abundance of basophilic cement lines and the streaks are separated from each other by relatively massive areas of bone

Case 284 s (growth 35 per cent) The microscopic picture is very similar to that in the foregoing case except that only small areas of suture tissue are seen Most of it shows a picture of an ossified suture In places isolated round areas of degenerative connective tissue are seen The bone is cancellous with relatively small cavities

The microscopic picture of the grafts which had grown the most revealed a complex massive meandering suture formation in which the longitudinal hairpin bends of connective tissue were separated from each other by long narrow bone spicules of the marginal bone This formation showed great osteogenic activity compared to the normal suture at the same age In the grafts that had grown least various degrees of ossification of the suture were seen

TRANSPLANTATION OF THE SUTURE TO THE THIGH

The results of transplantation of the coronary suture to the diaphysis of the femur in the rabbit are presented in table 14

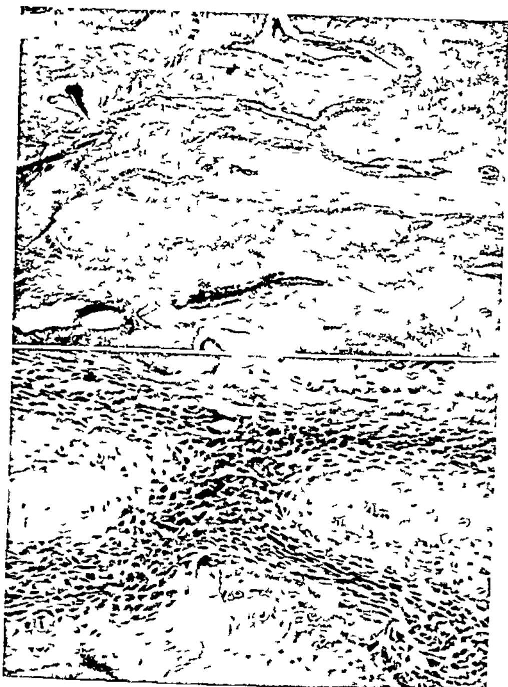


FIG 28 – Mi… opic structure of the suture graft in the fibula Dog no 241 Above the sutur… …massive structure in which the meanderings of the suture tissue enclose b… …and are separated from each other by bony spicules Below higher magnification … same The suture tissue is rich in cells and signs of intensive osteogenesis a… the bone margins

TABLE 14 — *Transplantation of the suture to the diaphysis of the femur in the rabbit*

Animal No	Age at operation (days)	Time of observation (weeks)	Growth of graft (mm)	Average growth of coronary suture in control group (mm)	Growth of graft in % of control sutural growth	Macroscopical and radiological observations		
						suture	fusion of graft to femur	special observations
61	18	26	(5)	6.5	77		not fused	d t l m rker e pelled
62	18	26	2	6 5	30		fused	pr m l h lf f sed to fem
63	18	26	9	6 5	138		not fused	
64	18	26	0	6 5	0		not fused	
251 d	*19*	*19*	*0*	6 5	0		fused	pr m l h lf f sed to f m
251 s	19	19	(12)	6 5	184	not visible	side to side	
252 d	19	19	(5)	6 5	77		fused	f tu femu good on
252 s	19	19	0	6 5	0		side to side	e ostos t of g ft
253 d	19	19	10	6 5	154		side to side	d t l m k pelled
253 s	19	19	(2)	6 5	31		not fused	both m kers pelled
254 d	19	19	(6 5)	6 5	100		side to side	d t l m k pelled tos
254 s	19	19	(5 5)	6 5	80		side to side	d t l m ker pelled

In 9 of the 12 experiments the distance between the markers had increased In only 2 cases (*62* and *253* d) had a branch like formation developed the growth of which corresponded to the increase in the distance between the markers In experiment *63* the transplant which had not fused with the femur showed significant growth In all the other 6 experiments either one or both of the markers had been expelled from the bone and in most ca es lay beneath the periosteum The graft was usually fused side to side with the femur and only slight signs of it were distinguishable The increase in the distance between the markers could not be interpreted as growth of the graft In no case was an open suture found

In figures 29 and 30 two examples of the experiments are presented

TRANSPLANTATION OF A PIECE OF CALVARIAL BONE WITHOUT SUTURE TO THE FIBULA

Th results of the transplantation of a piece of calvarial bone which did not includ the suture to the site of the excised proximal ECP of the fibula are

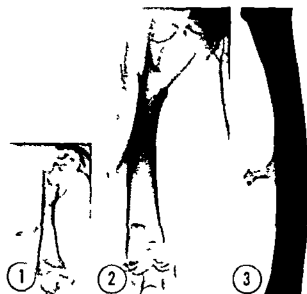


FIG 29 — *Suture graft at the diaphysis of the femur Rabbit no 62 X ray picture 6 days (1) and 10 weeks (2) after transplantation (3) The specimen A branch like formation has developed the growth in length of which was rather insignificant*

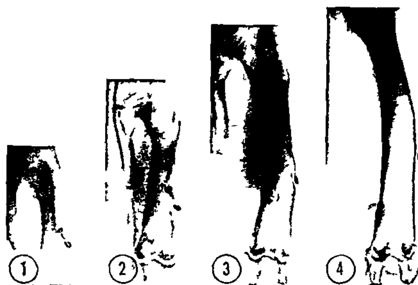


FIG 30 — *Suture graft at the diaphysis of the femur Rabbit no 251 s The graft gradually fu l side to side with the femur The increase in the distance between the marker ul ' n t be interpreted as growth of the graft*

presented in table 15 In no case was any growth of the graft noticed In the case *301* the distance between the markers had increased but this resulted from the expelling of one of the markers from the bone (see fig 31) The result in all cases was either a bone defect in the fibula or a curved bridge from the fibula to the diaphysis of the tibia In figure 31 an example of this type of trans plantation is seen

TABLE 15 — *Transplantation of a piece of calvarial bone without suture to the site of the excised ECP of the fibula in the rabbit*

Animal No	Age at oper ation (days)	Time of observ ation (weeks)	Distance between markers (mm) Initial	Final	Increase	Growth of fibular ECP (mm)	Growth of graft in % of epiphyseal growth
301	16	41	5 5	12	6 5	35 5[1]	19)
302	16	41	6 5	3 5	—3	55 [1]	0
303	16	41	6 5	6 5	0	37 [1]	0
321	28	29	7	7	0	28 5	0
322	28	29	7 5	7 5	0	24	0

[1]) control animal of the same litter
[2]) one of the markers expelled

DISCUSSION

In reimplantation experiments in both the rabbit and the dog the distance between the markers inserted at the margins of the graft had increased in some cases in a measure which corresponded to the normal growth of the suture In spite of the fact that only very slight variations in operative technique were possible the proportion of these cases was only 3/16 in the rabbit but 5/8 in the dog The result shows that preservation of growth is possible but on the other hand that growth is very easily disturbed

Bone defects in the rabbit were often seen at the margins of the graft but in the dog such defects were not found *Sirola* (1960) noticed that the repair of the calvarial defect was prevented if the dura mater was excised from the area of the trephine opening It is possible that minor lesions of the dura often manifested by slight haemorrhage at the surfaces during the operation could have caused the defects Because of the larger proportions of the dog such lesions could be better avoided in this animal No correlation between the occurrence of bone defects and the amount of growth was observed

When the suture was transplanted to the site of the excised ECP of the fibula it grew in the most successful cases many times as much as the suture normally

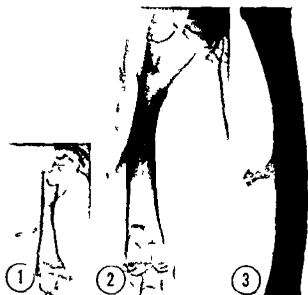


FIG 29 – *Suture graft at the diaphysis of the femur Rabbit no (2 X ray picture 6 days (1) and 10 weeks (2) after transplantation (3) The specimen A branch like formation has developed the growth in length of which was rather insignificant*

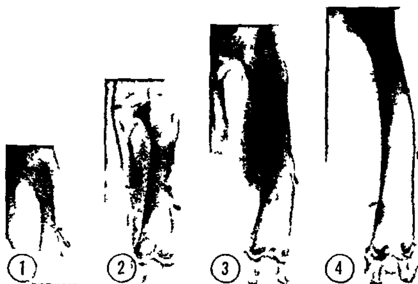


FIG [illegible] – *Suture graft at the diaphysis of the femur Rabbit no 251 s The graft [illegible] to side with the femur The increase in the distance between the [illegible] interpreted as growth of the graft*

graft as a substitute for the ECP From this point of view the comparison between the growth of the graft and that of the ECP is more useful

In some experiments on the rabbit the growth of the suture graft in the fibula was as great as that of the corresponding ECP of the fibula In two cases it grew even more than the control ECP In case *173* this result may have been caused to the control which was the fibula of another animal of the same litter In case *176* the growth of the graft was distinctly greater than that of the ECP of the opposite fibula As was shown in connection with the epiphyseal transplant the distance between the ECP of the tibia and the fibula increases during growth Therefore in fact a really successful suture graft should give as much growth in length as the ECP and epiphysis combined In table 2 (p 32) it is seen that the longitudinal growth of the epiphysis during the corresponding time is 3 5 mm This means that the ideal growth of the graft is 2 3 mm i e 0 5 mm more than the graft had grown

The initial alignment of the graft in the host area seemed to be as could be waited of importance for the end result

On the dog the suture graft gave 3/4 of the growth of the ECP at most The cause of the difference in results in the rabbit and the dog is not quite clear To understand the relative importance of the different factors possibly involved the course of histological events which are common to all autogenous bone transplants must be borne in mind The fact that the bone graft which includes the suture has been capable of growing must signify that the osteogenic cells of the suture have either survived or been replaced by host cells According to the literature it is probable that some at least of the connective tissue cells survive transplantation This also applies to the bone cells From the transplantation of the ECP we know that the survival of the germinal cells of the ECP seems to be essential for the preservation of growth capacity Applied to the transplantation of the suture it means that its success is dependent on the survival of the cells situated in the central layer of the suture

The survival of the graft cells on the other hand depends on the rapidity of restitution of nutrition i e revascularization In the present work the relative importance of the different pathways of revascularization of the suture reimplant was examined by placing a polythene plate in between the graft and the dura In the rabbit no growth occurred in such a graft This confirms the statement of *Treves Keith* that the nutrition supplied from the dura is more important than that coming from the periosteum In the dog the results was somewhat unexpected because the growth of the reimplant did not seem to be markedly disturbed This could be interpreted as meaning that the vascularization from the periosteum is relatively more important in the dog than in the rabbit

The size of the graft may to some extent account for the difference in the

results in the rabbit and the dog One might suppose that the revascularization of the larger graft in the dog would take longer than that in the rabbit This dependence has not been demonstrated before however Moreover the results of the epiphyseal transplantation in the first part of the present work speak against it

It is difficult to say whether the growth of the transplanted suture in the most successful experiments on the dog about 7 times as much as its normal growth signifies its maximal growth capacity At all events to give equally good results as in the rabbit the suture would have had to grow 9—12 times as much as it normally grows

The differences in the anatomy of the fibula between the rabbit and the dog were manifested in some phenomena noticed during growth When the growth of the graft was disturbed in the rabbit the shortening of the fibula corresponded to the disturbance of the growth It could also cause curving and shortening of the tibia if it had fused to the epiphysis of the latter In the dog disturbance of the growth of the tibia was uncommon Besides that the shortening of the fibula often bore no relation to the disturbance of the growth of the graft which was explained by the compensatory growth of the distal epiphysis This is clearly seen for instance in figure 25 (p 84) The phenomenon of compensatory growth has previously been noticed in animal experiments, e g by *Ollier* and *Silfverskiold*

The special character the acquired by suture graft after transplantation to the site of the ECP can be regarded as a manifestation of functional adaptation Its development could perhaps be understood in terms of the normal development of the serrate suture The formation of this is caused by localized apposition of bone at the two bone margins (*Weinmann & Sicher)* If the same phenomenon were to continue very intensively and for some length of time it is conceivable that the dents might grow much longer The suture in the grafts had a greatly increased number of hairpin bends as if the suture had been stretched In fact the forces acting on it were the same as those that normally act on the ECP of the fibula The mechanical forces acting on the graft exerted perhaps tension rather than pressure but this could be of no special significance because they were physiological

The suture when once adapted to its new position seemed to withstand the local mechanical stress well The fibula is naturally comparatively favourable as a host area because the bending forces and weight bearing in it are not heavy However an example of the fact that as a host area it does not essentially differ from the ulna for instance is provided by the following experiment performed on the dog (fig 32)

At the age of 26 days a suture graft was transplanted to the site of the excised distal ECP of the ulna A tiny piece of the epiphysis was left in situ After 26

weeks it was seen that the graft had grown enormously and been able totally to prevent the ulnar deviation of the carpus which results if growth is insufficient True this result was partly due to concomitant shortening of the radius The function of the limb was quite perfect

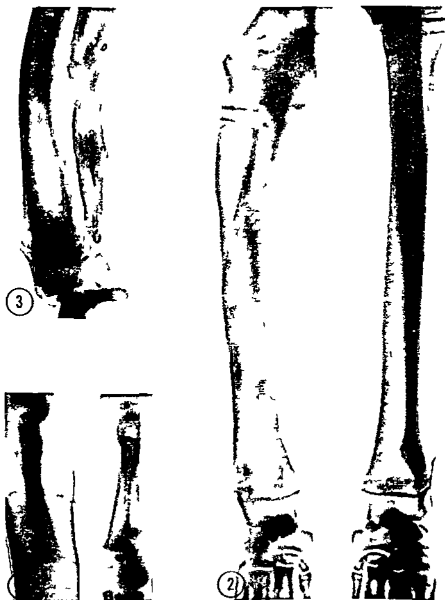


FIG 53 — Transplantation of the suture to the excised distal ECP of the ulna in the dog X ray pictures 2 days (1) and 26 weeks (2) after transplantation Note the increase in distance between the markers and the normal position of the carpus (3) X ray picture of the specimen

CONCLUSIONS

1 The coronary suture of the rabbit and of the dog may after reimplantation continue growth normally in favourable circumstances but the growth of the graft is very easily disturbed

2 The suture graft when transplanted to the site of the excised ECP of the fibula preserves its growth capacity in both the rabbit and the dog In the rabbit the suture graft may grow as much in length as the corresponding ECP of the fibula normally grows which corresponds to a 5 fold growth compared with that of the normal suture In the dog in the most successful cases the suture graft grew 3/4 of the growth of the corresponding ECP of the fibula This is about 7 times as much as the suture normally grows in the skull

These results signify that the suture has a potential growth capacity many times greater than is revealed in its normal site

3 The adaptation of the suture graft to its new environment is striking as is manifested by the considerable changes in its form and structure

SUMMARY

The main focus of the present work was the preservation of growth in autogenous growing bone grafts This problem is of clinical interest because a bone graft capable of growing after transplantation would be of value in the treatment of bone defects in growing long bones Two types of grafts were used epiphyseal cartilage and cranial suture

Transplantation of epiphyseal cartilage Besides the growth capacity the importance of the bony contact between the graft and the host bone was also studied Young rabbits and dogs were used as experimental animals On them a transplantation of the proximal ECP of the fibula to the corresponding site in the opposite leg or to muscle was performed

The growth of the graft was followed by X ray check ups The specimens were examined both radiologically and histologically The growth of the graft was compared with the normal growth of the ECP Both on rabbit and on dog the amount of growth was in some experiments as great as that of the control but more or less disturbed in the majority of cases The microscopic structure was normal in cases where the graft had grown well

The results were discussed in the light of the literature The following conclusions were drawn

1 The ECP of the fibula may when transplanted to the corresponding site in the opposite leg retain its full growth capacity Yet in spite of great care in technical performance some not easily definable factors very often cause a disturbance of growth

2 In successful cases the transplanted ECP does not differ from the normal in either appearance or structure at the end of the observation period

3 Without bony contact between the graft and the host bone only insignificant growth can take place in the graft

Transplantation of cranial suture In the second part of the work some features of a new type of growing bone graft were studied This was considered to be motivated because the clinical results of the transplantation of epiphyseal cartilage have not been very encouraging and also because there is a very limited source of autogenous grafting material of this type

The transplantation properties of the cranial suture were studied by reimplanting a bone plate including the suture and by transplanting it either to the site of the excised proximal ECP of the fibula or to the shaft of the femur In addition a number of control experiments of various types were performed Young rabbits and dogs were used as experimental animals The growth of the grafts and the structure of the specimens were studied by the same methods as in the first part of this work

The growth of the reimplanted suture was compared with the normal growth of the suture The growth of the suture graft transplanted to the fibula or to the thigh was compared both with the normal growth of the suture and with that of the fibular ECP

The results were discussed from various points of view The following conclusions were drawn

1 The coronary suture may after reimplantation continue growth normally but the growth of the graft is easily disturbed

2 The suture graft when transplanted to the site of the excised ECP of the fibula may preserve its growth capacity In the rabbit the suture graft grew as much in length as the corresponding ECP normally grows which corresponds to a 5 fold growth compared with the normal growth of the suture In the dog the graft grew in some experiments 3/4 of the growth of the corresponding ECP of the fibula This is about 7 times as much as the suture normally grows in the skull

The results signify that the suture has a potential growth capacity many times greater than is revealed in its normal site

3 The adaptation of the suture graft to its new environment was striking as was manifested by the considerable changes in its form and structure

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CORRECTIONS

Page 13 for *Wolff* (1892) place *Wolff* (1870)

Page 13 for *Kolliker* (1851) place *Kolliker* (1873)

Page 13 for *Humphry* (1861) place *Humphry* (1779)

Page 13 for *Biscard* place *Bisgard*

Page 21 for *Pereira* and *Dupertuis* place *Sousa Pereira* and *Dupertuis*

Page 52 line 14 for *Humphry* (1861) place *Humphry* (1779)

Page 53 line 9 for Sieffert place Siffert

Page 101 line 6 for 1914 place 1916

Page 101 in between the lines 15 and 16 add *Gudden* Experimentaluntersuchungen uber das Schadelwachstum Munchen 1874 Quoted by *Thoma*"

Page 105 in between the lines 26 and 27 add *Streloff* Beitrage zur normalen Knochenbildung — Zbl med Wissensch *10* 449 1872

Page 106 in between the lines 19 and 20 add *Wolff J* Ueber die innere Architektur der Knochen und ihre Bedeutung fur die Frage von Knochenwachstum — Arch Path Anat *50* 389 1870

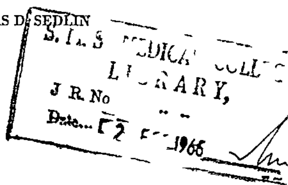
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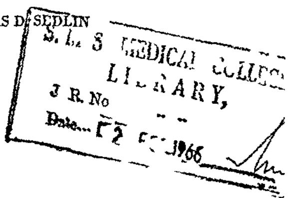
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SUPPLEMENTUM 83

From the Department of Orthopaedic Surgery
University of Goteborg Goteborg Sweden
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INTRODUCTION

The study of the physical properties of bone has been a subject of interest for more than a century the first contribution being attributed to *Wertheim* (1847) The considerable body of information which has accumulated during this time has been reviewed in recent years by *Evans* (1957) and *Knese* (1958) These surveys reflect that there are diverse opinions concerning the reaction of bone to mechanical forces This diversity is in part due to the fact that cortical bone is an heterogeneous or anisotropic material a feature which has been described in the works of previous authors (*Rauber* 1876 *May* and *Toaiari* 1937 *Carothers et al* 1949 *Evans* 1952 *Dempster* and *Liddicoat* 1952 *Evans* and *Lissner* 1959 *Smith* and *Walmsley* 1959 *Yamada* and *Motoshima* 1960 *Dempster* and *Coleman* 1961 *Yoshikawa et al* 1963 *McElhaney et al* 1964 *Sedlin* and *Hirsch* 1965)

Almost all previous studies have been directed toward the quantification of one or more physical properties Although many physical properties have been described or indicated for bone few attempts (*Currey* 1964 *Mack* 1964) have been made to explain the total behavior of bone as a material No attempt has been made to integrate this spectrum of properties into a matrix for the further study of the reaction of bone to mechanical forces One approach to integration is to develop a model in which the behavior of bone can be simulated by mathematical analogues and which can be modified and extended as new information is derived

For this purpose the author felt that the approach of the rheological field of physics offered potential as its concepts had been useful in the study of many materials and structures (*Reiner* 1960 *Stulen* 1962 *Papatian* 1962 *Johns* and *Wright* 1964) Rheology is concerned with the deformation and flow of materials and a rheologic model which represents bone does not involve the use of anatomic components With a model one might ultimately simulate experiments that are difficult to perform The application of this approach is the central theme of the thesis

In order to obtain valid information that could be used in the development of a model it was necessary to standardize the source material and testing methods The standardization required detailed study of the methods of preparing storing and testing specimens in order to ascertain the effects of multiple variables upon the results Since human post mortem material was easily available at this institution it was elected to use autopsy bone

This eliminated the problem of a sporadic source from biopsy and amputation material The femur was chosen for study since it is a representative long bone capable of yielding large numbers of samples

Quantitative data under defined *in vitro* conditions were obtained in the course of study These are not presented for their own sake, but are used in the demonstration of qualitative effects of variates for the standardization of methods and in the development for the model

CHAPTER II

MATERIAL AND METHODS

Source of material

This study was based upon 663 samples of human femoral cortex obtained from 43 autopsy subjects ranging in age from 14—91 years. The postmortem examination and specimen sampling was performed between 7 and 96 hours after death. Specimens were obtained as the needs of each experiment dictated in an attempt to minimize the time between sampling and testing. Although the effort was made to limit the sampling to previously normal subject (e.g. trauma cases) it was only infrequently possible to obtain bone from such subjects at the time needed. The subjects utilized for specimen source material thus represent a random selection of autopsy material available at this institution. The vital and morbid data for all subjects used in both quantitative and qualitative analyses in this study are listed in Table 1.

Site of sampling

Samples were prepared from mid femoral diaphysis for 75 per cent of the experiments reported here with upper and lower diaphysis providing material for the remainder. This distribution is noted in Figure 1 and it is seen that all samples for bending tests and some tension tests came from mid femoral diaphysis with tension and compression samples coming from upper and lower diaphysis.

Organization of material

The experiments with subjects contributing specimens are listed in Table 2. At the time of all experiments no information relative to the subject was available to the author save autopsy code number and age thereby resulting in "blind" type of testing. One group of experiments was planned to determine if changes being studied were present during most of adult life. For these experiments ten subjects ranging from 19—64 years of age were grouped. Twelve specimens were then prepared from each mid femur and site matched samples from all subjects were grouped resulting in twelve groups of ten specimens from ten subjects (Figure 2 A). These groups are referred to as Series Ten in the remainder of the text.

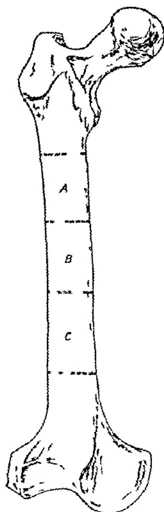


Figure 1 Site of Selection of Samples. The femur is divided into three zones A, B and C. Tension samples generally came from Zone A. All bending samples came from Zone B. Zone B was also used *in toto* for some compression tests. Zones C and A provided source material for compression blocks.

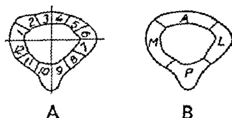


Figure 2. Cross section of Femoral Diaphysis. A. The site of sampling for the Series Ten. Twelve bending samples were prepared for each subject in the group and the corresponding samples for the ten subjects were studied as one test group. B. Indicates Anterior, Lateral, Posterior and Medial quadrants respectively for site coding of other samples with respect to quadrant of origin.

Subject Number	Sablg Hosp Numl
1	.01?
2	4908
3	4601
4	460
5	3603
6	330
7	3301
8	917
9	3001
10	3106
11	30
12	310
13	2301
14	1809
15	171
16	1 08
17	1703
18	1504
19	1411
20	1211
21	1006
[illegible]	1206
23	0906
24	1001
25	071
26	0606
27	0308
8	0 08
29	0 10
30	0 09
31	0009
32	9081
33	9803
34	—
35	9105
36	9507
37	9603
38	9011
39	8810
40	8808
41	8104
42	8106
43	731

[1] All times are

[2] CB = cantilev

BB = Suppor

LC = Comple

SC = Small c

T = Tens or

TABLE 2 *The Experiments and Studies*

Experiment Number	Description of Procedure	Page	Number of Specimens Used	Subjects Contributing
	The Effects of			
1	Freezing	20	74	15 [illegible] 41
2	Formalin	1	10	4
3	Alcohol	2	[illegible][1]	Series Ten
4	Short term air drying end supported samples	24	101	11 14 23 [illegible] 43
5	Short term air drying cantilever samples	26	10	Series Ten
6	Five day air drying and rewetting	27	1[illegible]	[illegible]7
7	Four day heat drying and rewetting	28	10	33
8	Short term wet heat	28	10	Series Ten
0	Short term dry heat	[illegible]	10	Series Ten
10	Four day heat drying	9	12	11 2[illegible] 43
11	Heat upon stress relaxation hysteresis	30	10[1]	33
1[illegible]	Grinding upon bone temperature	32	5	18 [illegible]1
13	Temperature changes during testing to failure	34	77	0 34 30
14	Temperature changes upon deflection of cantilever samples	36	10	Series Ten
15	Repetitive loading cantilever samples	37	30	Series Ten
16	Repetitive loading end supported samples	37	11	29
17	Variation in properties in different femoral quadrants	38	330[1]	8 9 11 14 1[illegible] 23 25 [illegible]8 34 36 38 39 41 43
19	Correlation of porosity and properties	41	1[illegible][1]	9 14 [illegible]3 [illegible]8
10	Demonstration of stress relaxation in different axes subjects	5[illegible]	71	Series Ten 1 [illegible] 3 6 7 1[illegible] 18 19 21 [illegible] 4[illegible] + Gp 17
0	The effects of different rates of deformation	54	[illegible]7	Series Ten 1 2 3 7 19 3[illegible]
21	Demonstration of hysteresis in different axes subjects	55	[illegible][1]	1 [illegible] 3 6 7 1[illegible] 16 19 [illegible] 31 35 40 Series Ten
	Deformation under a constant load	56	17	1 [illegible] 3 7 19 37
	Total Specimens Used		663[2]	

[1] Specimens utilized in toto or in part in other procedures

[2] Net total of all specimens duplication accounted for

Seventy eight samples were utilized in more than one test In these it was felt that prior testing would not interfere with the study that was under consideration

Choice of size of specimens

In studying the physical properties of bone some authors have used intact bones or large samples of bone (*Bell et al* 1941 *Marique* 1945 *Carothers et al* 1949 *Weir et al* 1949 *Evans* 1952 *Hirsch* and *Brodetti* 1956 *Lissner* and *Evans* 1956 *Evans et al* 1958 *Lease* and *Evans* 1959 *Vose* and *Kubala* 1959 *Hirsch* and *Frankel* 1960 *Frankel* 1960 *Evans et al*, 1962) while others have used small samples (*Wertheim* 1847 *Rauber* 1876 *Ohio et al* 1937 *Dempster* and *Liddicoat* 1952 *Evans* 1952 1957 1961 *Knese et al* 1955 *Smith J W* and *Walmsley* 1957 *Amprino* 1958 *Currey* 1959 *Hollinghaus* 1959 *Bassett* and *Becker* 1962 *Taysum et al* 1962 *Vose* 1962 *Ascenzi* and *Bonucci* 1964 *Mack* 1964 *McElhaney* 1964 *Hirsch* and *Evans* 1965 *Sedlin* and *Hirsch* 1965 *Smith R W* and *Keiper* 1965) Utilization of intact bones can minimize the time between obtaining the sample and actual testing and obviates some of the questions that arise from the use of small samples i e are the properties affected by removal from location in the cortex? However intact bones can vary greatly in their dimensions with resultant changes in some physical constants (e g moment of inertia) from place to place (*Koch* 1917 *Knese et al* 1955) with the result that it becomes difficult to reduce data to a standard basis for comparison (e g Kp/mm) of results The use of a small sample enables one to normalize data but incurs the potential objection concerning the removal of the sample from its location However there is some evidence that data from small samples are representative of the behavior of larger segments of a long bone (*Carothers et al* 1949) On balance this evidence coupled with the number of tests required led to the use of small specimens in this study

Preparation of specimens

After removal from the body segments of femoral diaphysis were worked fresh or stored at —20 C until such time as they could be worked The general method of preparation consisted of sectioning the femur in its long axis with a handsaw or bandsaw under a constant cold aqueous drip These strips were labelled according to their quadrant of origin (Fig 2 B) and could be further divided in their long axis The segments were then reduced to final size utilizing *underwater* machine and manual grinding *During preparation except when a specimen was actually being handled it was kept in Ringer s*

solution at room temperature Special shaping tools that were used in the reduction of longitudinal strips have been described elsewhere (*Sedlin* and *Hirsch* 1965)

Specimen size and shape

The size of specimens utilized in testing was varied several times during the conduct of this group of experiments with the type of test being performed being the chief determinant A specimen for a bending test in which both ends were supported and a central load applied usually measured 2 mm broad 1 mm thick and 30—40 mm long Occasional specimens measuring 1 × 1 30 mm or 2×2×40 mm were used in testing the effects of size or when extra or fewer samples were desired Specimens which were bent as cantilevers measured 1 7—2×1 7—2×50 mm in dimensions There was some variation in the size of bending specimens from lot to lot

A specimen for Series Ten was 3 5 mm in cross section dimensions with a moment of inertia of 1 mm^4

Specimens for tension testing consisted of rectangular planks with a reduced central area The standard size of specimens used in tests reported here was 50 mm long 2 mm thick 5 mm broad at the ends and 3 mm broad in the central reduced area which was 25 mm long The zone of transition from wide to reduced area was an arc 1 5 mm at either end

Specimens that were tested in compression were of two types 1) A complete cross section of mid femoral diaphysis 5 cm in length with ends which had been milled flat and parallel under 96% alcohol drip 2) A cube 5×10×15 mm which was first milled to approximate final size under 96% alcohol drip and subsequently ground under water

After preparation of a specimen was completed the cross section dimensions were determined with a friction release micrometer accurate to 005 mm All specimens with more than 1 5% variation in cross section dimensions were discarded or reworked After measurements were completed the specimen was ready for testing If possible the specimen was tested at this time Otherwise it was placed in Ringer s solution and stored at —20 C until testing

Testing equipment

The tests described in this study were performed on an Instron TT CM floor model tensile test machine (Figure 3) or with equipment described subsequently This machine has a capacity that enables one to test specimens under many conditions of loading (i e tension compression shear bending) through a wide range of loads and a wide range of rates of constant deforma

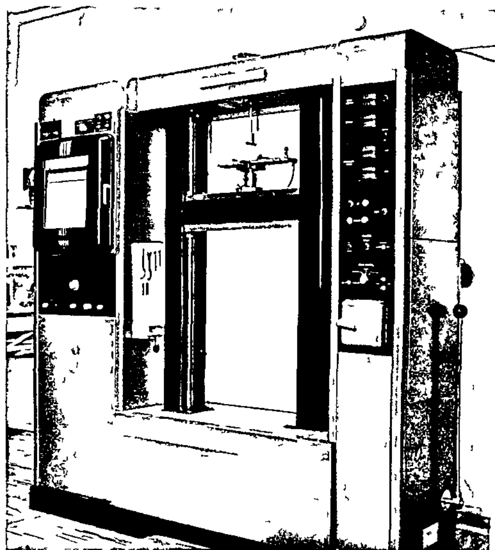
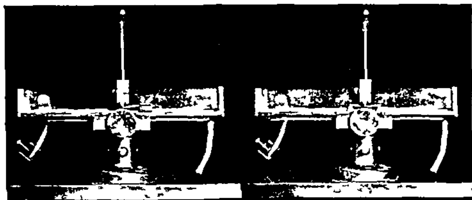


Figure 3 Instron Floor Model Tensile Test Machine Machine is shown with bending platform attached to cross bar At left the recorder is seen and on the right various controls and gauges

tion The load is applied via exchangeable cross heads (Figure 4) and load range is determined by interchangeable load cells with capacities ranging from 2 grams to 5 000 kg The rate of cross head movement can be varied from 02 cm/min up to 50 cm/min The speed of the recorder paper can be varied independently of the speed of cross head travel (rate of deformation) in order to magnify certain portions of the load deformation diagram Recording is via a servo controlled pen permitting a direct write load deformation

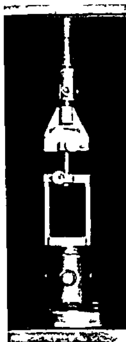


A B

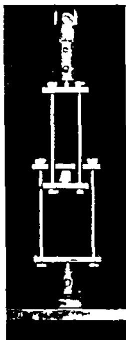


C

D



E



F

Figure 4 Loading heads for Instron used in this Study A & B The bending platform with front face removed Dangling tubes connect to water pump with heating element In A a specimen is being bent as a cantilever In B another specimen is being bent as an end supported center loaded beam C & D Closeups of specimen in A and B respectively E Set up for tension testing F The compression cage with a 5 cm segment of distal diaphysis The upper half of the cage is stationary while the cross bar moves downward carrying the lower half of the cage

diagram The scales of the load deformation diagram (Figure 5) were determined by the load cell being used and the ratio of recorder speed to speed of cross head travel If desired one can run the recorder while cross heads are stopped thus obtaining a direct record of the behavior of stress over time under a constant deformation The machine can also be made to cycle between two loads or two extensions enabling the observer to study deformation occurring between fixed loads or stress with known deformations All operations are accurate to $\pm 0.5\%$

By use of several different types of loading heads compression cantilever bending simple beam and tension tests were done The set ups for testing are shown in Figure 4

This machine is designed for tests requiring a constant rate of deformation or modifications It is not possible to apply an absolutely constant load or a constant rate of loading It is possible to provide a constant load $\pm 1\%$ but then one must rely upon readings of the scale of the machine to determine deformation over time An additional feature evolves from the speed of the recorder pen which requires 1 5 seconds to travel full scale Deformations occurring in stiff materials may be inaccurately recorded if small loads are used unless the specimen size is adjusted for this feature

In view of the necessity for absolutely constant load during the creep studies (page 56) and the desire for direct measurements of deformation

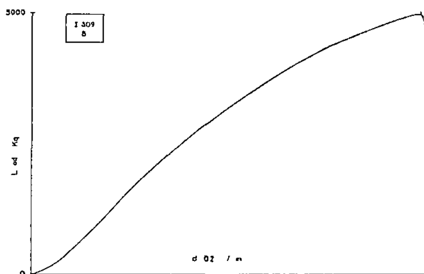
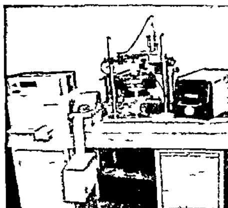
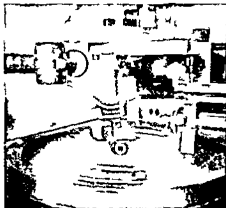


Figure 5 A load deformation diagram of a compression test to failure performed on a 5 cm segment of mid-diaphysis Failure is indicated by the vertical at top of diagram Subject identification is at upper left of chart The rate of deformation is indicated by d



A



B

Figure 6 Apparatus used in creep tests A Pictured from the left are voltmeter with printing readout recorder pump loading assembly with bottle of Ringer s solution at top amplifier B Close up of loading apparatus The specimen is in the center wrapped in a wick that is seen to come from a polyethylene tube at left and above The tube is connected to a bottle of Ringer s solution An initial siphon action soaks the wick and the specimen stays moist throughout the test The rope is led off into a trough to prevent fluid collection during the test At the right of the specimen the extension pickup can be seen When the weights are released the pick up registers the distance that the lower specimen clamp travels

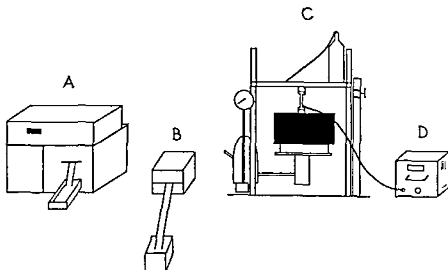


Figure 7 Diagram of creep test apparatus A Voltmeter with printing readout B Recorder C Test assembly Weights are indicated in black The pump is at the left of the assembly The loading unloading are performed by pumping the weights up to unload or down to load Specimen and bottle are as in Figure 6 D The amplifier with connection to extension pick up

a different apparatus was used for the creep tests This is pictured in Figures 6 7 The equipment consisted of a Taylor Hobson pickup amplifier and recorder plus a Hewlett Packard digital voltmeter with printing read out The voltmeter permitted readings of deformation accurate to 0 5μ while the recorder provided a direct deformation time curve over a 250μ scale (Figure 23 page 58)

Equipment for the determination of heat conduction in bone is described with the experiment

Methods of testing

The majority of the tests in this study were bending either as a cantilever or as a centrally loaded end supported beam (Table 2) The supports for the specimens in bending were provided by a special loading head for the Instron which had been designed to function as a clasimeter or cantilever load support This loading head has detachable sides enabling one to test under fluid or in air (Figure 8 9) All bending tests that were not done to determine the effects of drying were performed in Ringer s solution at either room temperature or 37 C The temperature was controlled ±1 and fluid exchanged via a cyclotherm pump

All tests except for the creep and heat measurement studies were performed in a special room with controlled temperature and relative humidity at 21 C±1° and 66%±2% respectively These were constantly monitored Prior to testing all specimens were heated to 37 C in Ringer s solution for one hour in a constant temperature bath unless the specific requirements of the test dictated room temperature and/or hydration

Compression specimens were tested in a modification of the Instron compression cage (Figure 4 F) It required 15—30 seconds to properly position the specimen in the cage for a compression test

Tension specimens were first tested utilizing specially designed holding clamps which were lined with silicon carbide paper to prevent slipping (Figure 4 D) Subsequently a fine groove pattern was cut on the faces of the clamps and it was found that this worked as well as the silicon carbide paper in preventing slipping with the clamps holding loads up to 100 kg in some cases The groove pattern was preferred since this eliminated the need for changing sandpaper This type of clamp was improved in the creep studies equipment in that one face was morticed to receive a specimen which simplified the procedure of accurate alignment of the specimens The tension specimens required approximately 2—3 minutes to position and carefully align in the vertical axis of the load

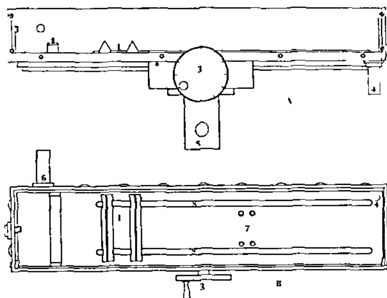


Figure 8 Diagram of bending platform A Front view showing supports for specimen (1) Note the tiny studs that project from the top of supports These aid in alignment of the specimen (2) Support for baffle to reduce fluid turbulence (3) Control handle to shift entire platform (4) Exit port for fluid (5) Stand for connection to machine B Top view showing (6) Entrance port for fluid (7) Holes for anchoring of cantilever attachment (8) Track on which supports (1) can be shifted

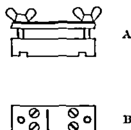


Figure 9 Diagram of cantilever attachment for the bending platform A Front view showing slots for track B Top view of lower half of attachment showing an alignment wire that facilitates seating of the specimen

If not otherwise stated all tests indicated in the text are bending tests to failure performed with unfixed end supports and progressive central load at a rate of 1 cm/min Specimens for tension which were tested to failure were deformed at rates of 1–5 mm/min More rapid rates were not feasible since the recorder speed was too slow to record deformation in the usual samples used The usual rate of deformation for compression tests was 5 mm/min

a different apparatus was used for the creep tests This is pictured in Figures 6, 7 The equipment consisted of a Taylor Hobson pickup amplifier, and recorder plus a Hewlett Packard digital voltmeter with printing read out The voltmeter permitted readings of deformation accurate to 0 5μ while the recorder provided a direct deformation time curve over a 250μ scale (Figure 23 page 58)

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Tension

$\sigma = P/A$ where A is the original cross section area at the fracture site and $E = \sigma/\epsilon$ where P and ϵ were measured from the most linear portions of the load deformation diagram or calculated from a portion of the curve at an estimated 25% of the ultimate strength

Other

Energy absorption in bending was determined by planimetric measurement of the area under the load deformation diagram and appropriate conversion utilizing load paper speed and specimen size

Notation

σ = Stress
ϵ = Unit strain
P = Load
I = Moment of inertia
E = Modulus of elasticity
L = Original length of specimen or test area
M = Maximum moment
A = Cross section area of specimen or test area
B = Breadth of specimen
D = Depth of specimen
c = Distance from neutral axis to fiber of greatest stress
y = Deflection in bending

CHAPTER III

SOME FACTORS THAT EFFECT THE PHYSICAL PROPERTIES OF BONE

The following features incident to the preparation and evaluation of physical property data from cortical bone samples are considered in this chapter
The effects of methods of storage
The effects of varying the conditions of preparation and testing
The effect of repetitive loading
The influences of site of sampling age and microanatomy
An interim summary is presented at the end of the chapter

The effects of methods of storage

Since it is apparent that some time must elapse between obtaining a specimen and its testing the possibility exists that a change takes place in the physical properties during this period If so one must either test the specimen quickly after obtaining the sample or preserve it in order to minimize the change

Of the three common methods of preserving specimens only fixation with formalin has received much attention No systematic studies of the effects of freezing and alcohol have been performed *Frankel* (1960) noted no difference in the breaking strength of femurs that had been frozen *Carothers et al* (1949) found that embalming increased the bending strength in rat femurs *Calabrisi* and *Smith* (1951) stated that embalming for 40–60 days decreased the compressive strength of human tibial cortical samples about 13% *McElhaney et al* (1964) studied the effect of embalming on beef femoral samples and found that there was a significant 12% reduction in the compressive strength but very little upon tensile strength maximum strain and modulus of elasticity *Evans* (1964) showed that embalming increased the tensile strength of human tibial samples With this information as background the following experiments were done

Several properties after freezing

Seventy four specimens either 2×1 mm or 2×2 mm in cross section dimensions from subjects 15 28 & 41 were prepared as rapidly as possible after obtaining the bone Forty three were tested three hours after removal from the body and thirty one were frozen at

—20 C for 3 to 4 weeks The e were tested after thawing and heating to 37 C Care was taken to site match specimens in order to have representative samples from all quadrants present in both groups The results are summarized in Table 3 There is an unequal number of specimens in the two groups due to the inability to obtain equal numbers of specimens from all quadrants of the three femurs

TABLE 3 *The Effect of Free ing upon some Physical P operties of Bone*[1]

Condition	No of samples	Ultimate Fiber Stress Kp/mm²	Modulus of Elastic ty Kp/mm² × 10³	Energy Ab sorbed to failure Kpcm/mm × 10⁻⁷	Total Deflection to failure mm
Fresh	43	16 7±3 0	1 41± 24	9 16±2 72	1 81± 64
Frozen	31	17 6±3 –	1 39± 23[2]	9 6 ±3 0 [2]	1 60± 3[2]
Probabil ty		> 05	> 05	> 05	> 05

[1] — All values presented for a phys cal property are mean values with one standard deviation ind cated by ±

[2] — Only 23 specimens are represented in these groups due to some difficulties with recording apparatus Val d maximum stress values could be derived but other properties could not

It can be seen that freezing and subsequent heating to 37 C had no signi ficant effect upon the physical properties in the combined data Also there were no significant differences between fresh and fresh frozen specimens in each of the individuals These observations coupled with those of *Frankel* lead to the conclusion that the physical properties of bone are not altered by freezing at —20 C

Modulus of elasticity after formalin fixation

Ten tension specimens from subject 42 were prepared fresh the filet size in these samples being 2×2 mm and 20 mm long They were tested at room temperature without prior warming They were de formed at a rate of 2 mm/minute until a load of 8—9 kg was reached This load approximated a unit stress of 2—2 3 kp/mm The speci mens were unloaded and placed in 10% formalin solution for three weeks and then retested Tangent moduli of elasticity were calcu lated and the differences were analyzed for each specimen

The average E value for the samples in the fresh state was 400±54

Kp/mm²* After three weeks in formalin solution it was 417±41 Kp/mm This 4 3% increase in the modulus of elasticity was suggestive but not significant (10>p> 05)

The findings are in agreement with those reported by *McElhaney et al* (1964) as regards the tensile deformation In view of the reports cited earlier it appears that formalin or embalming solutions may affect some properties and not others Accordingly, it was felt that this means of preservation should not be used

Deformation after alcohol fixation

Fifty five specimens from Series Ten set up as cantilevers were used in two experiments All had been frozen prior to testing Most had been been previously tested in checking other variables In the first experiment 30 of the specimens were thawed at room temperature and placed in 40% alcohol for 10 days and tested Then they were placed in Ringer s solution for 3 hours and retested For the second experiment 25 specimens were thawed and tested at room temperature in Ringer s solution Then they were placed in 40% alcohol for 5 days and tested again after which they were replaced in Ringer s solution for 24 hours and retested

Specimens were deformed at a rate of 1 cm/min up to a load of 100 grams in every test This load resulted in an average maximum bending moment of 3 Kpmm and a resultant average maximum stress of 3 Kp/mm² Deflection that occurred at 100 grams load was determined for each test

The results were as follows In the first group 24 showed less deformation in alcohol than in Ringer s solution The average decrease was 03 mm representing a change of 4% This difference was significant beyond the 1% point (t_9=3 12) For the group of 25 specimens the mean deflection in the first test was 76 mm after 5 days in alcohol it was 74 mm and after replacement in Ringer s solution it was 73 mm The 2 5% decrease in deformation after 5 days in alcohol was significant beyond the 1% level (t_4=3 307) But unlike the first group these specimens failed to show an increase in deformation after being replaced in Ringer s solution

The effects of immersion in Ringer s after soaking in alcohol observed in the first experiment could not be duplicated in the second phase of the second experiment Inasmuch as it could not be stated that the effects of alcohol were reversible it was not employed as a preservative in the study

* One standard deviation If not otherwise indicated all mean values are presented with one standard deviatiation in the remainder of the text

The effects of varying the conditions of preparation and testing

In the course of specimen preparation and testing several operations introduce factors which could influence results Experiments in this section examine the effects of four of the possible variables — air drying heat exposure temperature changes during grinding and temperature variations at the time of testing

The effect of air drying

The effects of air drying on physical properties have been more frequently discussed than the other factors noted above *Wertheim* (1847) showed that stress and strain in dry bone were more nearly proportional than in fresh samples *Pauber* (1876) found that drying increased the tensile and compressive strength of human femoral samples *Bell et al* (1941) stated that drying in air produced no significant alterations in the bending and torsional strength of intact rat femora *Evans* and *Lebow* (1951) showed that air drying increased the modulus of elasticity hardness and tensile strength of human femoral samples but decreased the shearing strength and energy absorbing capacity *Dempster* and *Liddicoat* (1952) found that drying increased the tensile strength of cortical samples and confirmed Wertheim s finding that the stress strain curve to failure is more nearly linear in dry bone *Smith* and *Walmsley* (1959) showed a 7% increase in the modulus of elasticity after one hour of air drying in one human sample They also showed that progressive loss of weight of a bone sample occurred upon removal from the body In addition they showed that longitudinal contraction occurred progressively up to five hours in drying another sample of bone *Lease* and *Evans* (1959) noted a decrease in the fatigue life of some metatarsals and an increase in the fatigue life of others associated with drying *Dempster* and *Coleman* (1961) found increases in the ultimate tensile and bending strength of dry tibial samples both parallel and at right angles to the long axis of the osteons *Evans* (1964) in another study showed that drying increased the tensile strength of femoral samples *Ascenzi* and *Bonucci* (1964) showed that drying increased the tensile strength of single osteons

The weight of the evidence indicates that dry bone is stronger and deforms less than wet bone Implicit in several of the studies is the probability that some changes due to air drying are reversible With the exception of the studies of *Amprino* (1958) and *Smith* and *Walmsley* (1959) little work has been done relative to the reversibility of the drying process Since specimens in this study were kept wet during preparation and were tested wet it

would appear of little moment to test this feature However to determine the effect of drying upon physical properties not previously studied and to confirm earlier work the following studies were performed

Several properties after variable periods of air drying

One hundred thirty seven samples from subjects 11 14 23 25 and 43 were prepared but 12 specimens were used in the heat experiment described on page 29 Insofar as possible the specimen groups con sisted of one specimen from each quadrant of each subject s femur Thus a basic group consisted of 20 specimens Specimens from 4 of the subjects were 2×1 mm in cross section dimensions while speci mens from the fifth subject were 2×2 mm All specimens were 30 mm in length and tested to failure as centrally loaded end supported

TABLE 4 *The effect of air drying upon ultimate fiber stress in bending*[1]

Time in air	Subjects					Average
	11	14	23	25	43	
Wet	21 3	21 2	19 2	19 2	13 4	18 9
15	24 6	19 2	17 5	20 9	17 1	19 9
30	19 1	22 8	20 5	22 1	19 2	20 7
45	22 2	23 3	20 9	22 7	19 3	21 7
60	26 0	26 2	19 4	24 0	19 5	23 0
Average	22 6	22 5	19 5	21 8	17 7	0 8

Analysis of Variance

Source of Variation	Degrees Freedom	Sum of Squares	Mean Square
Total	24	197 [illegible]5	8 2[illegible]
Subjects	4	93 35	23 34
Time in air	4	51 74	12 94
Residual	16	[illegible] 16	3 26

$F_{4,16}$ subjects = 7 16 $p <$ 01

$F_{4,16}$ air time = 3 97 05 $> p >$ 01

[1] All values are mean values for all samples from a subject for a given state of time in air Comparison of individual values would have necessitated the introduction of a third variate — location within the femur Units are Kp/mm²

TABLE 5 *The effect of air-drying upon the modulus of elasticity in bending*[1]

Time in air	Subjects					Average
	11	14	23	25	43	
Wet	1 85	1 97	1 57	1 76	1 28	1 69
15	1 90	1 44	1 30	1 66	1 38	1 54
30	1 60	1 65	1 38	1 64	1 47	1 55
45	1 58	1 73	1 31	1 62	1 42	1 53
60	1 56	1 72	1 28	1 70	1 37	1 52
Average	1 70	1 70	1 37	1 68	1 38	1 57

Analysis of Variance

Source of Variation	Degrees Freedom	Sum of Squares	Mean Square
Total Variation	24	9412	0 392
Subjects	4	6017	1504
Time in air	4	0919	0230
Residual	16	2476	0155

$F_{4,16}$ subjects $= 9\ 703$ $p <\ 01$

$F_{4,16}$ time in air $= 1\ 484$ $p >\ 05$

[1] Values are stated in units of $Kp/mm^2 \times 10^3$ Derivation of values as in Table 4

beams at a deformation rate of 1 cm/min Span thickness ratios were 20 1 in the smaller specimens and 15 1 in the larger specimens All specimens were tested at room temperature One group was tested submerged and other groups were tested after being air dried for periods of 15 30 45 and 60 respectively Twenty five specimens were tested after air drying of five or ten minutes The ultimate fiber stress tangent modulus of elasticity energy absorbed to failure and total deflection to failure were calculated These results are partially summarized in Tables 4 5 and 6

It can be seen from Tables 4—6 that there were significant differences between subjects for each of the properties that were measured The only significant change related to time in air was the increase in ultimate fiber stress The analysis for total deflection to failure was similar to that of elastic modulus and energy absorption Significant differences could be demonstrated between subjects but not between various states of hydration The specimens tested after five or ten minutes of air drying did not show any changes

Deformation after four days of dry heat

Ten specimens measuring $2 \times 2 \times 50$ mm from subject 33 were tested fresh in Ringer's solution at room temperature Afterwards each was placed in a glass sandwich and dried for four days at 105 C Then they were retested dry replaced in Ringer's solution for 24 hours and tested again The specimens were loaded as cantilevers 30 mm in length to 250 grams at a rate of 0 5 cm/min After measuring the deformation in the three instances tangent moduli of elasticity were calculated for every specimen in each condition Since shrinkage sufficient to change the average moment of inertia by 13% occurred after heat drying it was necessary to evaluate E instead of deflection Differences in individual specimens were compared

The mean modulus of elasticity in the initial test was $1\ 34 \pm 14 \times 10^3$ Kp/mm In the second test this value was $1\ 56 \pm 24 \times 10^3$ Kp/mm² After rewetting it became $91 \pm 15 \times 10^3$ Kp/mm The differences in values for individual specimens were significant on inspection Testing of the differences showed $t_9 = 7\ 515$ for the change due to heat drying $t_9 = 7\ 836$ for the decrease in deformation after rewetting $t_9 = 11\ 447$ in the comparison of the original test and the rewet test

Deformation after one hour of wet heat

This study utilized one group from Series Ten which was tested as cantilevers with a length of 30 mm After immersion in Ringer's solution at room temperature the specimens were loaded to 100 grams Subsequently they were boiled in Ringer's solution for one hour replaced in room temperature Ringer's solution for 30 minutes and then retested Next they were put in the refrigerator for 24 hours and tested again at room temperature in Ringer's solution The deflection occurring at each loading was determined and compared for each specimen

The average deflection was 66 mm for the initial test compared to 63 mm for the group after boiling and cooling The differences in individual specimens were of borderline significance ($t_9 = 1\ 455$) The mean deflection increased to 70 mm after 24 hours in Ringer's solution but the change compared to the values of the control group was of borderline significance ($t_9 = 1\ 788$)

Deformation after one hour of dry heat

The third study utilized another group from Series Ten Test conditions were similar to those in the previous experiment except that the specimens were heated in an incubator for one hour at 105 C

After evaluation the results observed were similar but more pronounced and consistent than those in the boiling experiment The average deflections were 69 mm in the control test 65 mm after heating and immediate rewetting and 7[illegible] mm twenty four hours later These differences were significant (t_9 immediately after rewetting was 287 t_9 the next day = 2 245)

Several properties after four days of dry heat

The material in this experiment consisted of twelve specimens from subjects 11 2[illegible] and 43 They were sandwiched and placed in an incubator for four days at 105 C After removal they were center loaded end supported and tested to failure Other conditions of testing were as on page 24 Ultimate fiber stress modulus of elasticity energy absorbed to failure and total deflection to failure were calculated for each specimen The group data were compared to wet controls from the air drying experiment on page 24 The data are summarized below in Table 7

TABLE 7 *Changes in Physical Properties due to Heat Drying*

Hydration State	Number Samples	Ultimate fiber stress Kp/mm	Modulus of Elasticity Kp/mm² × 10²	Energy absorbed to Failure Kp cm/mm² × 10	Total Deflection mm
Wet	3	18 [illegible] ± 4 3	1 64 ± 3[illegible]	[illegible] 14 ± 3 [illegible]1	[illegible] 03 ± 4
Oven dried	1[illegible]	1 [illegible] ± 3 1	[illegible]8 ± 37	0 1[illegible] ± 044	4 ± 06
Probability		> 0	< 001	< 001	< 000

It can be seen that heat drying at 105° C for four days significantly affected the modulus of elasticity energy absorbed to failure and total deflection to failure parameters but it did not significantly alter the breaking strength These results in bending tests are in essential agreement with those of *Evans* and *Lebow* (19[illegible]1) for tension tests In addition the load deflection diagrams for the dry specimens were almost linear to failure whereas wet specimens showed a major change at 40–50% of the breaking load (Fig 10)

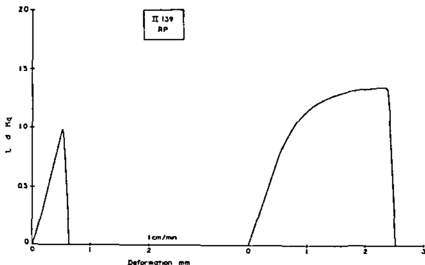


Figure 10 Bending load deformation diagrams to show the effects of 4 day heat drying At the left is the diagram for a specimen which had been heated to 105 C for four days At the right is its site matched counterpart tested in the wet fresh state The rate of deformation is indicated by d

The four experiments as a group indicated that bone is permanently altered when subjected to 100—105° C for one hour It appears that elevated temperature and dehydration produce a more pronounced effect than heating or drying alone The effect of heat drying for days and subsequent rewetting in the first experiment was to decrease the modulus of elasticity by 32% and as was shown on page 27 the effect of drying at room temperature for the same time and rewetting was to decrease E by 5% This feature was supported by the one hour tests in which it was shown that boiled specimens had a deflection increase of 6 1% twenty four hours later and oven heated specimens registered an 8 7% increase It is felt that the effects of temperature elevation may vary with the length of exposure to heat but the point at which the permanent changes begin has not been determined

Stress relaxation and hysteresis after four days of dry heat

Ten $2 \times 2 \times 50$ mm specimens from subject 33 were tested as follows (1) wet in room temperature Ringer s solution (2) dry after incubation for four days at 105° C (3) wet in Ringer s solution twenty four hours later The specimens 30 mm in length were arranged as cantilevers The hysteresis test was performed by loading the specimens to 250 grams and then unloading from this point at rates of 0 5 cm/minute After two minutes without changing the position of the specimen the stress relaxation test was conducted In these

the specimen was loaded to 250 grams the excursion of the load heads stopped and the recorder allowed to run for one minute In effect the deformation in a specimen was held constant while the re corder registered the change in resistance of the specimen over time These operations were repeated on every specimen for the three conditions

In each test it was possible to measure the decrease in stress in each speci men after one minute and the residual deformation in the cycle testing when the specimen registered no resistance The changes in area within the loops were obvious (Fig 11)

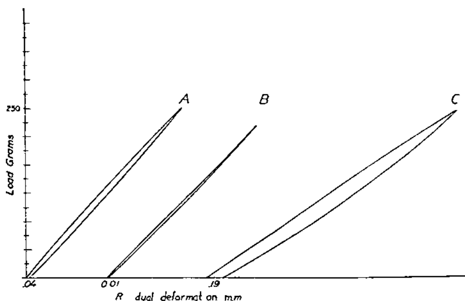


Figure 11 Hysteresis loops of one sample Left control test in Ringer s Center after five days at 105 C Right replacement in Ringer s The residual deformation at zero load is indicated on the abscissa See text for experimental method

In the hysteresis tests the average residual deformations at zero stress were 0 05 mm for the control group 0 01 mm for the heat dried group and 0 21 mm for the rewet group These changes were highly significant The differences in the hysteresis loops for the three conditions are obvious in Figure 11 In the stress relaxation tests the average decreases in stress after one minute were 4 3% in the control test 2 1% in the incubated group and 13 4% in the rewet group Again the changes were highly significant

Measurement of heat

The above demonstration of the effects of heat on physical properties indicated that temperature changes during the specimen preparation process should be investigated When *Rafel* (1962) measured the heat produced in mandibles by dental burrs he observed that the longer the application of frictional stimulus the more widespread the heat effect and the longer the dissipation period The highest temperature he measured some 3 mm from the cutting surface was 24° C *Thompson* (1958) found that bone temperature could rise from 38°—67° C as the speed of drilling increased

In this study the only processes which might have raised the temperature of specimens above 37 C were machine grinding and milling Since the milling blades always felt cool immediately after use due to cooling with 96% alcohol it was felt that the bone surface temperature remained below 37° C during the process As a similar statement could not be made regarding the surface temperature after machine grinding under water the following experiment was performed

Bone temperature during underwater grinding

Into five compression blocks from subjects 18 and 21 three Honeywell thermocouples 0 1 mm in diameter were introduced through holes which had been drilled just large enough to accommodate the lead and insulating jacket The thermocouples were placed at varying distances from the potential grind surface (Figure 12) The specimens were mounted in a vise and put in a pan filled with room temperature water (23° C) A fourth thermocouple was placed in the water The four thermocouples were connected to an amplifier which in

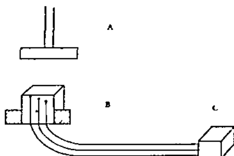


Figure 12 Diagram of apparatus used in measuring of heat during grinding A Grind stone which was lowered at a constant rate B Bone specimen with the thermocouples inserted C Amplifier

turn was linked to a four-channel recorder This permitted simul taneous reading of temperature changes at three points within the specimens and in the surrounding fluid Grinding was performed with a carborundum wheel which was put in contact with the bone surface and then lowered at a constant rate

The set up was calibrated for 40 C and 100 C by placing a steel die which had been heated to the appropriate temperature on the surface to be ground and recording the changes The conditions of the tests conducted were

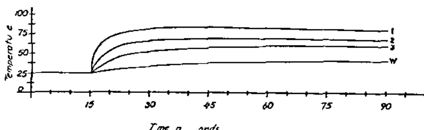
1 Intermittent grinding with approximately ten seconds between operations in increments of 0 1 mm at 2800 rpm grinding carried out parallel to the long axis of osteons and continued until the thermocouples were destroyed

2 Constant grinding parallel to the long axis of the osteons with a wheel rate of 2800 rpm and bone grinding rate of 02 mm/sec grind ing continued until all thermocouples were destroyed

3 Constant grinding of two specimens perpendicular to the long axis of the osteons other conditions as in 2

4 Constant grinding parallel to the long axis of the osteons at a wheel rate of 1000 rpm bone grinding rate 0 02 mm/sec

The results were as follows With a surface temperature of 100 C the calibration curves showed that the specimen temperature ro e to 83 C at a distance of 0 4 mm from the surface to 65 C at 1 3 mm from the surface and to 55 C at 2 7 mm from the surface (Figure 13)



F gure 13 Calibration curves at 100 C A steel die at 100 C is placed on the bone sur face 15 seconds after the recording has begun The three thermoelements within the bone sample 1 2 3 then registered temperature rises as indicated as did the elem nt in water W The distance of the thermoelements from the surface is as in the text

With a temperature of 40° C at the surface these temperatures were 36 C 32 5° C and 29 C respectively As would be expected the time at which each element registered its maximum rise varied directly with the distance from the heat source The grinding procedures demonstrated that the surface temperature did *not* rise above 40° C irrespective of the grinding plane In the intermittent grinding test there was no temperature increase until the respective thermoelements were approximately 0 1 mm from the grinding surface During the constant grinding tests the temperature in all elements slowly rose as they approached the grindstone (Figure 14) The results support *Rafel s* observation that with intermittent grinding and adequate water cooling bone temperature tends to remain at the level of the surrounding fluids All grinding tests proved that the process utilized in specimen preparation did not produce an elevation greater than 40 C anywhere in the specimen

The effect of testing at different temperatures

Smith and *Walmsley* (1959) in reporting observations on two samples of bone stated that the value for Young s modulus was inversely proportional to the temperature and that the effects of temperature variation in the range tested (40°—110° F) were fully reversible Other information relative to the effect of this variable on bone testing is lacking Due to its obvious importance the following tests were performed

Several properties at two temperatures

Seventy seven specimens approximately 1 5×1 0×25 mm from subjects 9 34 and 39 were used They were divided into two groups care being taken to site match samples in both groups One group was tested in Ringer s solution at 21 C and the other group tested at 37 C All specimens were tested to failure at a rate of deformation of 1 0 cm/min with distance between supports of 20 mm The ultimate fiber stress modulus of elasticity total deflection to failure and energy absorbed to failure were calculated for both groups

The data as summarized in Table 8 indicated little difference in the values obtained for ultimate fiber stress modulus of elasticity and energy absorbed to failure whether testing at 21° C or 37° C There was however a significant increase in the total deflection to failure at 37 C It is possible that a small change in a property might be masked by variation in individual specimens This possibility was controlled in the next experiment

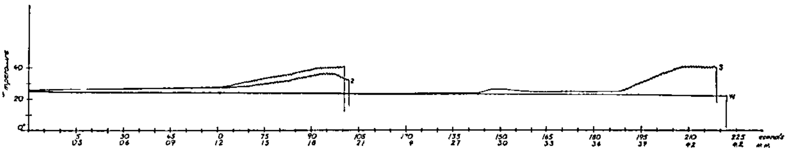


Figure 14 One set of curves obtained during the grinding process with set up as in Figure 12 Grinding begins at the left side of diagram and continues until the 3 thermoelements are destroyed as indicated by the sudden drop below the base line

TABLE 8 *The Effect of Temperature Upon Some Bending Properties of Cortical Bone*[1]

Temperature	No of samples	Ultimate Fiber Stress Kp/mm²	Modulus of Elasticity Kp/mm² × 10³	Total deflection to Failure mm	Energy Absorbed to Failure Kpcm/mm²
21 C	41	20 1±2 5	1 72± 23	1 47± 38	121± 037
37 C	36	20 6±2 9	1 72± 2[illegible]	1 69± 53	126± 040
Probability		> 05	> 05	05>p> 01	> 05

[1] All values are mean scores presented with one standard deviation

Four curves were discarded for calculation of values other than ultimate fiber stress thus there are 39 and 34 values respectively in the other groups

Deformation at two temperatures

First one group of specimens from Series Ten was placed in Ringer s solution at 27 C and tested then they were warmed for one hour in 37 C Ringer s solution and retested The specimens were tested as cantilevers with a length of 30 mm up to a load of 100 grams at a rate of 1 0 cm/min Deformation occurring in both instances was determined and the differences in individual specimens analyzed The specimens had an average deformation of 0 77 mm at 21° C and 0 82 mm at 37 C The moduli of elasticity changed accordingly from 1250 Kp/mm at 21° C to 1190 Kp/mm at 37° C These differences were significant (t_9 differences=3 028)

The observations in this experiment thus confirm *Smith* and *Walmsley* s finding of a decrease in the modulus of elasticity associated with an elevation in temperature It is reasonable to conclude on the basis of the observations in this pair of experiments that deformation in bending samples is greater at 37 C than at 21° C The magnitude of this change 6% might be small enough to be obscured in those tests in which identical specimens were not used Thus there might be an effect of temperature upon the breaking strength but it would require an inordinate number of subjects and samples for demonstration

The effect of repetitive loading

Clinically it has long been known that bones fatigue and fail with constant repetitive loading *Smith* and *Walmsley* (1957) stated that repeat stress well below the ultimate strength ultimately causes a fatigue fracture and that the number of stress applications necessary is an inverse function of the

magnitude of the stress *Evans* and *Lebow* (1957) found the average fatigue life of 15 femoral samples tested in bending to be approximately 1 2 million cycles under a constant load of approximately 3 5 kp/mm *Lease* and *Evans* (1959) performed fatigue studies on intact human metatarsals and demonstrated fatigue failures from 1 000—14 000 cycles with 15 lb loads Since repetitive loading was employed in the current experiments to determine the effects of variables upon the physical properties a question naturally arises concerning its possible influence on the results This problem was checked by the following formal tests and by observations in the course of other tests

Repetitive loading of cantilever beams

Three groups from Series Ten were repetitively loaded ten times as follows one group was loaded to 100 grams with thirty seconds between loads the second group was loaded to 100 grams with 3 5 seconds between loads the third group was loaded to 200 grams with thirty seconds between loads Tests were performed in Ringer s solution at room temperature with a deformation rate of 1 cm/min and beam length of 30 mm The specimen positions were not changed between loadings The average stress values were 3 kp/mm² in the 100 gram tests and 6 kp/mm² in the 200 gram tests

The deformation resulting from the loads above was determined for the 300 tests The average deflection from the applied load in the first group for the first loading was 69 mm and at the tenth loading 68 mm This decrease was not significant In the second group the average deflections were 64 mm in both instances In the third group average deflection for the first loading was 1 25 mm and for the fifth and tenth times 1 23 mm No significant changes were noted before the fifth load Thus 1 7% decrease in deflection occurring at the fifth load was significant (t_0 differences—5 013)

Repetitive loading of centrally loaded, end supported beams

Eleven end supported bending specimens from subject 29 were loaded repetitively four times to 500 grams at a rate of 1 cm/minute Specimens were approximately 1 75×1 75 mm in cross section dimensions and were tested over a support length of 27 mm This load produced an average maximum fiber stress of 3 83 kp/mm The average deformation was calculated in each case and was found to be almost identical in the first and fourth loads in all specimens

From the two experiments, it can be seen that bending specimens can be reloaded without any effect if a small unit stress is maintained It is felt that there is some limiting unit stress which will result in permanent deformation with repetitive loading This limit is not defined here since it is expected that it will vary from bone to bone and subject to subject (*Sedlin* and *Hirsch* 1965) These data do not mean that repetitive loading can be carried out indefinitely without effect even with the small loads utilized for these tests have not set an upper limit regarding the number of times a specimen could safely be reloaded It is concluded with unit fiber stresses in the 3—4 Kp/mm range that specimens can be safely reloaded at least ten times when set up as cantilevers and four times when set up as end supported centrally loaded beams

The influences of site of sampling, age and microanatomy

Site of sampling

Physical properties have been repeatedly demonstrated to differ from individual to individual bone to bone and in different parts of the same bone in many investigations utilizing a variety of techniques (*Carothers et al* 1949 *Calabrisi* and *Smith* 1951 *Evans* and *Lebow* 1951 *Evans* 1957 *Yamada* and *Motoshima* 1960 *Evans* 1964 *Hirsch* and *Evans* 1965) It is apparent that physical properties of bone cannot be discussed in terms of the actual values without citing the location of the source of specimens Samples which had been tested wet as end supported centrally loaded beams with the same constant rate of deformation were analyzed with respect to site within the mid femoral diaphysis In Tables 9 and 10 it can be seen that there are differences in physical properties which can be attributed to source within the mid femur On the basis of the data it can be stated that the posterior quadrant samples are weaker and have a lower modulus of elasticity than samples from other quadrants which do not differ significantly from each other The findings here relative to weakness of posterior quadrant samples are in agreement with those of *Maj* (1938) In five of the subjects specimens from both femurs were tested Analysis of these values failed to demonstrate significant differences in right and left femur although the numbers of specimens available for the comparison were small

As would be expected from the data in Tables 9 and 10 there is a high correlation between ultimate fiber stress and the modulus of elasticity in bending samples from the mid femur The data presented elsewhere (*Sedlin* and *Hirsch* 1965) showed a product moment correlation coefficient of + 81

TABLE 9 *Changes in Ultimate Fiber Stress in Bending Samples Grouped According to Location Within the Mid Femoral Diaphysis*[1]

Subject	Quadrant of Origin				Mean
	Posterior	Lateral	Anterior	Medial	
9	18.[illegible]	19.4	20.8	18.3	19.3
11	19.[illegible]	23.1	23.8	19.5	21.[illegible]
14	20.9	21.9	[illegible]9	[illegible]0	21.9
15	1[illegible]	1[illegible].3	1[illegible]9	16.4	1[illegible]
[illegible]3	18.3	[illegible]0.6	18.3	20.1	19.[illegible]
25	1[illegible]	[illegible]0.[illegible]	19.8	19.8	19.[illegible]
28	19.8	20.4	19.0	19.6	19.[illegible]
34	[illegible]0	[illegible]3.0	18.0	20.4	[illegible]0.[illegible]
36	16.6	18.2	1[illegible].6	1[illegible].9	17.6
38	18.1	18.3	19.[illegible]	19.1	18.8
39	20.[illegible]	[illegible]0.8	21.[illegible]	2[illegible].3	21.3
41	9.6	11.5	11.8	12.4	11.3
43	14.0	1[illegible].9	15.1	1[illegible].6	15.2
Mean	1[illegible].8	19.3	18.9	18.7	18.[illegible]

Analysis of Variance

Source of Variation	Degrees Freedom	Sum of Squares	Mean Square	F	Probability
Total	51	460.73	9.03		
Subjects	12	404.[illegible]5	33.69	29.30	< .01
Location	3	15.[illegible]	5.08	4.41	< .01
Residual	36	41.23	1.15		

[1] All values are reported in Kp/mm² and here are presented as mean values for all samples from a quadrant for a subject 336 individual tests are represented in the table

which was highly significant and the following estimating equations were derived

$$\sigma = 4.0 + 9.45E$$

$$\hat{E} = 264 + 06975\sigma$$

where σ and $\hat{E}$ = estimated stress and modulus of elasticity respectively

These findings are in agreement with those of *May* (1942) in his study of human bending samples *Toaiari s* (1937) study of mule metatarsal bending samples and *Weir et al* (1949) in a study of intact rat femora

TABLE 10 *Changes in Modulus of Elasticity in Bending Samples Grouped According to Location Within the Mid Femoral Diaphysis*[1]

Subject	Quadrant of Origin				Mean
	Posterior	Lateral	Anterior	Medial	
9	6 53	6 25	7 38	5 96	6 53
11	6 83	7 80	7 55	6 39	7 14
14	6 60	6 47	7 98	7 72	7 19
15	5 69	5 55	5 53	5 70	[illegible] 49
23	5 14	5 52	5 62	5 77	5 51
25	6 31	7 10	6 99	6 73	6 78
28	6 44	6 9[illegible]	6 09	7 15	6 6
34	6 71	7 52	6 05	7 04	6 83
36	5 47	5 83	5 49	6 16	5 74
38	6 54	6 75	6 76	7 24	6 8[illegible]
39	6 86	6 28	7 12	6 60	6 7[illegible]
41	3 56	4 34	3 99	4 55	4 11
43	5 38	5 71	25	4 94	3[illegible]
Mean	6 00	6 31	6 29	6.27	6 2[illegible]

Analysis of Variance

Source of Variation	Degrees Freedom	Sum of Squares	Mean Square	F	Probability
Total	207	15 3393	0 0741		
Subjects	12	9 2803	0 7734	25 36	< 01
Location	3	0 2012	0 0671	2 20	≅ 10
Residual	192	5 8578	0 0305		

[1] Values are $Kp/mm^2 \times 1000$ This analysis was carried out utilizing four values for each quadrant for each subject with occasional insufficient values being substituted by randomization Each value reported should be multiplied by 25 for a mean value for a quadrant or subject

Age

May (1942) when studying bending strength of central diaphysial samples of multiple human bones felt that there was a parabolic relationship between age and strength in adults with low points in the 25—30 and 60—80 age groups but there was considerable variation in the data presented *Hoch et al* (1959) demonstrated a decrease in the maximum transverse compressive load of the middle of the shaft of long bones with increasing adult age *McElhaney* (1964) stated that the ultimate strength of compact bone decreased after

age 26 Yet *Evans* and *Lebow* (1951) were unable to detect differences in the tensile and shearing strength of adult femoral samples with advancing age A similar finding was reported by *Ascenzi* and *Bonucci* (1964) regarding the strength of single osteons Other investigations (*Hollinghaus* 1959 and *Vose et al* 1961) have tended to indicate that the intrinsic strength of bone samples increases with advancing age

Analysis of some data from this study presented elsewhere (*Sedlin* and *Hirsch* 1965) and in Tables 9—12 demonstrated no trend with respect to age The inconclusiveness of these findings coupled with the disagreement noted in the literature does not mean that physiologic age is not a determinant of physical properties Rather a systematic study in which other variates are standardized needs to be done before valid conclusions can be drawn

Microanatomy

May (1938) in studying bending samples of bull bone reported no correlation between porosity of samples and bending strength when the porosity (Haversian canal volume) was less than 50% *Evans* (1958) felt that a sample with a few large osteons and irregular fragments would have a greater tensile strength than a sample with a larger number of small osteons and fragments This statement while valid as a generalization accounting for the differences between fibula and femur did not account for differences in samples from the same bone *Currey* (1959) stated that bone without Haversian systems had a greater tensile strength than bone with Haversian systems and calculated a strong negative correlation ($r = -0\ 6629$) between tensile strength and percentage of 'Haversian system type bone present *Vose* (1962) found no correlation between ultimate yield loading and the size and frequency of Haversian canals

The question of the effect of porosity was studied by preparing sections from 125 specimens from four subjects that had been tested to failure under identical conditions At least four cross sections from each specimen were prepared by *Frost's* techniques (1958 1959) Specimens were selected for study on the basis of disparity in breaking strength so that approximately equal numbers of specimens with high breaking strength and low breaking strength were studied The average Haversian canal volume of each specimen was determined by previously reported methods (*Hennig* 1958 *Sedlin et al* 1963 *Sedlin* and *Hirsch* 1965) and this value was expressed as a percentage of the volume of the specimen

It was found that there was no correlation between the Haversian canal volume and individual values for ultimate fiber stress and energy absorbed

to failure in the majority of the specimens examined At the extreme values of porosity — less than 2 5% or greater than 15% — an inverse relationship was noted with the breaking strength but this relationship involving less than 20% of the specimens was far from absolute There was a weak corre lation between porosity and the modulus of elasticity but it was not signif icant These findings substantiate those of previous authors indicating little relationship between Haversian canal volume and physical properties Yet it cannot be concluded that the porosity of bone samples is not an important determinant of the physical properties The problem is too complex to be accounted for solely by determination of the porosity volume (*Sedlin* and *Hirsch* 1965)

Ohro et al (1937) found that bending specimens which had a higher proportion of vertical or steeply oriented collagen fibrils had a higher modulus of elasticity and a higher resistance to fracture than specimens which had circular or obliquely oriented fibrils *Toaiari* (1937) stated that resistance to fracture was greater where the collagen fibrils were parallel to the axis of the test section than when they diverged *Evans* (1958) agreed with these findings and suggested that the greater the number of cement lines in a specimen the weaker the bone will be According to *Ascen i* and *Bonucci* (1964) the ultimate tensile strength in single osteons with a marked longi tudinal arrangement of fiber bundles in successive lamellae is higher than those with fiber bundles running alternately so that their direction in suc cessive lamellae changes through an angle of about 90 Thus there appears to be agreement insofar as bending and tension are concerned on the fact that a general longitudinal orientation of fiber bundles provides greater strength than divergent or oblique orientation

Consideration of the difficulties of *Ascen i* and *Bonucci* (1964) in locating osteons with a longitudinal course discloses another feature to be noted In adult bone osteons have straight vertical paths for short distances if at all Constant branching and overlapping produces an irregular pattern in cross section Therefore in a tension test some osteons will be pulled in their long axis while others will be subjected to shear compression or bending A reasonable conclusion therefore is that a study of the relationship between microanatomy and physical properties in small samples presents a complex problem in three dimensional reconstruction

Interim summary

1 Freezing of samples of cortical bone has no effect on physical properties when tests to failure are done

2 Preservation of samples in formalin may produce an increase in the modulus of elasticity in tension testing

3 Preservation of samples in alcohol decreases the deformation of bending samples an effect that may or may not be reversible

4 Air drying of samples has the following effects in bending
   a Increase the ultimate fiber stress after one hour of drying
   b Increase the modulus of elasticity after five days of drying
   c Decrease or no change in the modulus of elasticity after one hour of drying
   d Decrease in the modulus of elasticity after rewetting

5 Heating of bending samples to 100—105 C has the following effects
   a Decrease the ultimate stress fiber but not significantly in specimens tested dry
   b Significantly increase the modulus of elasticity decrease the energy absorption to failure and the total deflection to failure in specimens tested dry
   c Significantly decrease the modulus of elasticity in specimens tested after rewetting
   d Decrease stress relaxation hysteresis and residual deformation after cyclic loading in specimens tested dry
   e Increase the parameters above (d) after heat drying and rewetting

6 Drying at room temperature or 105° C produces significant changes in the size of small samples

7 The permanent effects of temperature elevation and drying combined are greater than either alone

8 Cortical bone transmits heat quickly at least as far as 3 mm from the heat source

9 Temperature does not rise above 40 C when bone is ground under water

10 The deformation of bending samples is significantly greater at 37 C than at 21 C No changes are noted in the ultimate fiber stress and the energy absorbed to failure

11 Bending samples can be loaded repetitively at least ten times as cantilevers and four times as end supported beams if unit stresses are maintained in the 3—4 Kp/mm range

12 The posterior quadrant of the mid femur has a lower ultimate fiber stress and modulus of elasticity than other quadrants

13 A high correlation exists between the ultimate fiber stress and the modulus of elasticity in bending samples

14 A definite association between physical properties and chronologic age is not seen

15 Little or no correlation between the Haversian canal volume and physical properties has been observed in 125 samples

CHAPTER IV

DERIVATION OF A RHEOLOGIC MODEL FOR BONE

Introduction

In the broad sense rheology is that branch of physics which is concerned with the deformation and flow of materials It deals with all materials save the theoretically ideal liquid and absolutely rigid solid The goal of rheology is to predict the forces necessary to cause a given body to flow or deform or prediction of the flow or deformation that will result from a known combination of forces The concepts to be presented in this section are relatively old in the realm of theoretical mechanics The author has utilized standard works in the rheological literature for definitions and organization (*Jaeger* 1956 *Reiner* 1958 *Reiner* 1960 *Fredrickson* 1964) The following represents an attempt to place the study of physical properties of bone into the theoretical frame of reference of rheology

Fundamental rheologic properties

There are four fundamental rheologic properties of materials — (1) elasticity (2) viscosity (3) plasticity (4) strength The majority of more complex material properties can be described by combining the fundamental properties in various ways Fundamental properties and the complex properties that can be derived from them are termed *essential properties* (*Reiner* 1958) First consider the fundamental properties bearing in mind that *all real materials possess each property although quantitatively the amount of each property may be negligible*

Elasticity

Elasticity is defined as that property of a material which enables it to recover from a deformation produced in the material by an external force In a *perfectly elastic solid* all deformation is recovered upon release of the external forces and strain is proportional to stress for all stresses A suitable model for the perfectly elastic solid is a spring as in Figure 15 A stress strain diagram will be a straight line (Figure 15) and the following relation between stress (σ) and strain (ϵ) is present

$$\sigma = E\epsilon \tag{1}$$

where E is an elasticity constant for the material

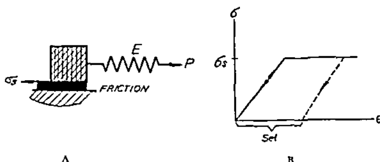


Figure 18 The Perfectly Plastic Solid or Prandtl Substance A This is symbolized by a Hooke spring linked in series to the St Venant friction element This substance will have elastic deformation below the yield point of the plastic and above this will have an indeterminate plastic flow This is pictured in B if the stress is discontinued at some time the elastic part of the material will then recover however there will be permanent deformation This is indicated by the *set* noted on the abscissa

Complex Properties

The idealized bodies just cited rarely exist in nature in pure form — i e the Hookean Newtonian St Venant and Prandtl substances are not to be found as isolated materials By linking the elements more complex behavior can be described *If the elements are linked in series each element then takes the same total load and the deformation is additive If the elements are linked in parallel each element takes a part of the load while the deformation in each is identical* The models already shown or to be described refer to elongations in tension but can be modified to depict shear linear and cubic dilatations The equations that are presented refer to uniaxial tension but they can be adapted to other stress conditions

In consideration of complex properties the combination of a Hookean spring and Newtonian dash pot in parallel and in series merits detailed examination since these combinations form fundamental units of more complex models

First consider a spring linked in parallel to a dash pot Figure 19 and the properties represented by the

Kelvin body or firmoviscosity

The term firmo viscosity or solid viscosity is applied to that property exhibited by an elastic material which exhibits resistance to deformation in addition to elastic resistance The model presented (Figure 19) is appro

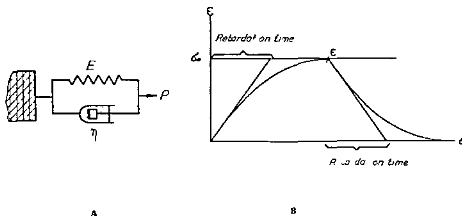


Figure 19 The Firmo Viscous Substance or Kelvin Body A. A spring is linked in parallel to a viscous element If a constant stress σ_0 is applied a strain time diagram will be as in B The deformation is not attained instantaneously but exponentially approaches some final deformation, the time required being dependent upon the constants for the spring and dashpot The relationship of the constants for the dash pot to the spring determines the amount of damping of instantaneous deformation which can be obtained This is the retardation time If at some certain deformation the stress is discontinued the body recovers its original length again with damping of instantaneous recovery as in the application of the load This body eventually recovers all deformation

priate for cork Some aspects of the behavior of this model are as follows From eq (1) and eq (2) the following relationship is evident

$$\sigma=E\epsilon+\eta\frac{d\epsilon}{dt} \tag{4}$$

If a constant stress (σ_0) is applied at time $t=0$ when $\epsilon=0$ the total strain will be given by

$$\epsilon=\frac{\sigma_0}{E}\left\{1-e^{-\frac{Et}{\eta}}\right\} \tag{5}$$

Therefore the strain σ_0/E which would be reached instantaneously in the case of a perfectly elastic substance is approached exponentially as in Figure 19 Thus there is a delay in the attainment of the final deformation Materials characterized by this model vary in the time required to reach total deformation The *retardation time* is a material property defined as the time at which $1/e$ of the final deformation has yet to be achieved This delay in attaining total strain under a constant stress is termed *elastic fore effect* Upon release of the load the strain decreases exponentially to zero according to

$$\epsilon=\epsilon_0 e^{-\frac{Et}{\eta}} \tag{6}$$

4

where ϵ_0 equals the strain at release of load. The time at which $1/e$ of the initial deformation is unrecovered is given by η/E. This delay in recovery is termed *elastic after effect* and the combination of elastic fore effect and elastic after effect is termed *delayed elasticity*. To recapitulate, the Kelvin body is characterized by absence of instantaneous elasticity, an elastic fore effect and elastic after effect, no change in stress under a constant deformation, and ultimate recovery of all deformations.

Now consider a spring *linked* in *series* with a dash pot and the properties described by

The Maxwell body or elastico viscosity

The model is shown in Figure 20 and is appropriate for pitch and concrete. Since the total strain (ϵ) is the sum of strain in both elements and the same stress acts on both elements, eq. (1) and (2) yield

$$\frac{d\epsilon}{dt}=\frac{d\sigma/dt}{E}+\frac{\sigma}{\eta} \tag{7}$$

If a constant stress (σ_0) is applied to this material when it is unstrained initially, the strain satisfies

$$\epsilon=\frac{\sigma_0}{E}+\frac{\sigma_0 t}{\eta} \tag{8}$$

so that there will be an initial elastic strain (σ_0/E) that is instantaneous followed by an increasing viscous strain which is linear and a strain time curve is as seen in Figure 20. The instantaneous elastic strain is recoverable but the viscous deformation is not. This model will deform permanently with the smallest stresses. Under a constant strain (ϵ_0) there is a decrease in stress in the model according to

$$\sigma=E\epsilon_0 e^{-\frac{Et}{\eta}} \tag{9}$$

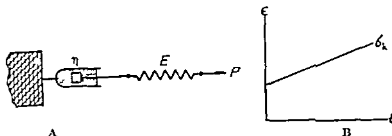


Figure 20. The Elastico Viscous Substance or Maxwell Body. A. The model is a spring linked in series to a dash pot. Relationships of this model are discussed in the text. It can be seen that with a constant stress the material will have initial instantaneous deformation due to the elastic element and secondary progressive deformation due to the viscous damper. A strain time diagram will be as in B.

This phenomenon is called stress relaxation The relaxation time is a constant for the material and equal to the time in which stress decreases to $1/e$ of its original value It can be seen from eq 9 that stress under a constant strain will tend to zero

Thus the Maxwell body and the property of elastico viscosity can be characterized by instantaneous elasticity followed by progressively increasing deformation under constant stress an exponential decrease in stress under constant deformation and some permanent deformation after any stress

The elements just described fundamental and complex can be combined to describe different behavior By various combinations most material properties can be depicted thus providing a framework for a more complete analysis of the material s properties

Experiments

The preceding chapter demonstrated that the physical properties of cortical bone could be altered by many factors In the introduction to this chapter some of the parameters by which a material is described were indicated It can be seen that in order to characterize cortical bone its behavior in a variety of circumstances must be determined In this section specific experiments that were necessary to further characterize cortical bone as a material are described

The behavior of bone under a constant deformation

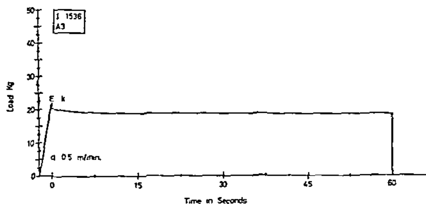
The test material included the following

One group from Series Ten tested as cantilevers 16 specimens from six subjects tested in tension twenty five specimens from 14 subjects tested as end supported beams five complete cross section segments of femur from five subjects tested in longitudinal compression and 15 compression blocks from the same subjects tested in compression

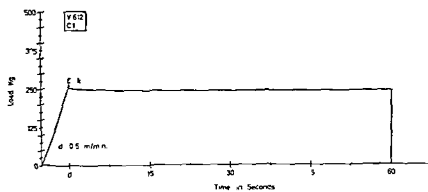
The constant deformation was applied by loading the specimens at rates varying from 0 2 cm/min to 1 0 cm/min the rate being varied according to the size of specimen and type of load being applied When the load reached an estimated 25% of the ultimate failure load the progressive loading was stopped and the resultant deformation was maintained while the recorder was kept running Thus stress as a function of time with deformation held constant was recorded The recording time was varied from test to test Each test was watched and the recording discontinued when it became evident that no further change was occurring The predominant recording time was 30 to 2 , but this was extended to 10 to 15 periods in certain instances in order to confirm the fact that additional changes were not occurring

The *qualitative* result was *identical* in all specimens from all subjects When deformation became constant (i e loading stopped) a decrease in stress occurred with 50—60% of the decrease being apparent at 30 Sample curves are shown in Figure 21 The curves all were asymptotic to some new level but none tended to zero There were quantitative differences in the amount of decrease in stress in time according to the axis of loading but these differences are not germane to the issue since they undoubtedly furnish another example of the heterogeneity of bone

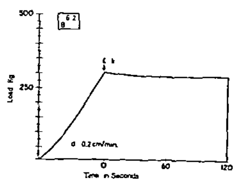
This experimental group in addition to the experiments cited on page 30 thus demonstrate that *stress relaxation* is a phenomenon present in bone and that bone has a relaxation time as a material property Stress relaxation



A



B



C

Figure 21 Stress relaxat on in cortical bone A. A tension test The specimen is deformed at 0 5 cm/minute until a load of 20 kg is reached The progressive loading is then stopped and the deformation held constant indicated by $\epsilon = k$ The recorder then registers the decrease in stress during the next 60 B A test in compression on a 5 × 10 × 15 mm block C A test on a 5 cm segment of central diaphysis

has been noted in muscle (*Stacy et al*, 1955 *Schottelius* 1957) joints (*Johns* and *Wright* 1964) skin (*Ridge* and *Wright* 1964) and was previously stated to occur in bone (*Smith* and *Walmsley* 1957)

Changes in the deformation of bone at different rates of deformation up to a constant load

One group from Series Ten twelve cantilever specimens from subject 35 and five tension specimens from five subjects were used in this experimental group Cantilever specimens from Series Ten were loaded to 100 gms first at a rate of 0 1 cm/min then at rates of 1 0 cm/min with two minutes being allowed between loads They were then refrigerated over night and the tests repeated the following day but this time they were loaded at a rate of 1 0 cm/min at the first trial and 0 1 cm/min on the second trial Two minutes were allowed for recovery between trials and the specimen position was not changed between trials Specimens from subject 35 being larger than the Series Ten group were loaded to 250 grams first at a rate of 1 0 cm/min and then at 0 1 cm/min As with the Series Ten specimens two minutes was permitted for recovery and the specimen position was not changed between loads Tension specimens were loaded to 10 kg first at a rate of 0 1 cm/min and then 0 2 cm/min More rapid loading rates were precluded due to the relatively slow speed of the recording as noted in Chapter II Unit stress approximated 3 5 kp/mm in the cantilever specimens and 8 kp/mm in the tension tests Deformation occurring at the different rates of loading was determined and the differences analyzed

In the Series Ten group the average deformation was 86 mm in the first test at rate of 0 1 cm/min and 0 82 mm at a rate of 1 0 cm/min The following day when the specimens were tested with the more rapid rate initially mean deformation at 1 0 cm/min was 0 85 mm and at 0 1 cm/min 0 87 mm The differences in individual tests were highly significant in both instances ($t_9=4\ 56$ first test $t_9=3\ 56$ second test) In the 12 specimens from subject 35 mean deformation at the rate of 0 1 cm/min was 1 36 mm and at the rate of 1 0 cm/min the deformation was 1 27 mm These results were consistent and highly significant ($t_{11}=6\ 90$) The results were similar in the tension group i e mean deformation at 0 1 cm/min was 11 mm while at 0 2 cm/min it was 09 mm The individual differences were significant ($t_4=2\ 412$)

These results for cantilever bending and tension demonstrate that bone deforms less with rapid loading conditions than with slower conditions *McElhaney* (1965) demonstrated similar behavior in testing compression

samples of human and bovine bone at more rapid rates of loading than were used here It is thus evident that deformation of bone is some function of the rate of deformation and that the modulus of elasticity of bone is in reality a range of values

Behavior of bone during loading and unloading at different constant rates

Twenty five cantilever specimens from 2 subjects a group from Series Ten, five compression blocks from 3 subjects 15 simple beam specimens from 2 subjects and 10 tension specimens from 5 subjects were used to study this feature The test machine was programmed to cycle between zero load and 50% of full scale with appropriate small loads being cho en for each type of specimen (100 or 250 gms for a cantilever test and 100 kg for a compression block) Two tests were performed on each specimen one at 0 1 cm/min or 0 2 cm/min and the second at 1 0 cm/min

The general shape of the hysteresis loops differed according to the axis of loading but in all tests a loop was described and the findings were similar An example of one pair of loops is seen in Figure 22 The steeper more nearly linear curve at the more rapid rate of loading is to be expected from the preceding experiment It was shown in the previous chapter that the residual deformation could be affected by previous heating of bone The

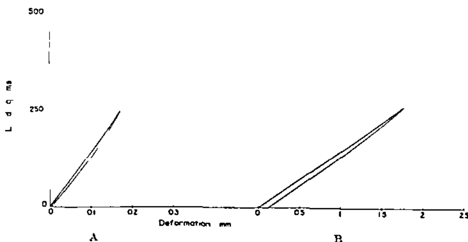


Figure 2 The effect of different deformation rates upon hysteresis in bending samples A The specimen was loaded at a rate of 1 0 cm/minute up to a load of 250 grams and then unloaded from this point B The same specimen at a rate of 0 1 cm/minute Note the decrease in residual d formation at zero load in test A

new feature that was demonstrated by these tests was the fact that the amount of residual deformation varied with the rate of deformation More residual deformation was present at zero stress at the slower rate than at the more rapid rate These hysteresis loops thus indicate that more energy is dissipated in this type of testing with a slow rate as compared to a more rapid rate

The characteristics of bone deformation under a constant load — creep studies

Part 1

This was a preliminary investigation using 4 tension samples from subject 37 tested on the Instron machine with the machine programmed to deliver a constant load $\pm 1\%$ Each specimen was tested first at 5 kg and then at 10 kg These loads represented approximate stresses of 0 85 and 1 7 kp/mm^2 respectively The constant load was maintained for 30 and readings of deformation were made at 1 2 3 4 5 15 and 30 The load was released at 30 and 30 were allowed for recovery before the second load was applied

It was seen with the 5 kg loads that the final resultant deformation was attained almost immediately in each specimen at least within the accuracy of the readings in this set up ($\pm$ 01 mm) and did not change throughout the test period With the 10 kg loads deformation increased up to 10 after application of the load and thereafter appeared to remain constant These findings led to the preliminary conclusion that total deformation under a constant stress is approached asymptotically and deformation is a function of stress duration However the experimental procedure did not permit determination of whether or not the specimens returned to original length after removal of the load In addition some features of the deformation under a constant stress could have been lost in the accuracy of the readings These problems were surmounted in Part 2

Part 2

Five tension specimens from five subjects were tested using the equipment described on page 15 Readings of deformation were accurate to 0 0005 mm Two specimens were loaded successively with 5 kg 10 kg then 20 kg and 30 kg loads Three specimens were loaded successively with 10 20 and 30 kg loads All specimens were 3×2 mm in cross section in the 25 mm reduced area As with the earlier tests the applied load was maintained for 30 and then released Deformation was recorded constantly

TABLE 11 *Changes in Deformation Over Time Under Differing Constant Loads*[1]

Subject	Load Kg	Loaded: Initial Deformation	Loaded: 5	Loaded: 15	Loaded: 30	Unloaded: Initial Recovery	Unloaded: 5	Unloaded: 15	Unloaded: 30
1	5	24 0	24 5	24 5	[illegible]4 5	0	0	0	0
	10	26 4	31 8	32 3	32	3 8	1 8	1 1	[illegible]
	20	8[illegible] 1	89 4	91 3	9[illegible] 7	13 6	0	5 4	4
	30	154 2	182 6	192 5	198 9	42 4	[illegible]6 9	24 1	3[illegible]
2	10	55 0	59 8	60 5	60 [illegible]	5 1	3 5	[illegible] 6	0
	20	1 0	[illegible]4 6	[illegible]6 0	[illegible]8 0	2 6	0	0	0
	30	98 7	104 1	106 3	108 2	11 8	3 9	[illegible]	[illegible]2
3	10	83 3	86 3	86 9	87 4	3 4	0	0	0
	20	146 3	1 0[illegible]	173 1	1[illegible]5 3	20 1	9 9	8 1	6 9
	30	207 4	31 9	24[illegible] 4	261 4	51 8	29 6	26 1	24[illegible]
7	5	11 5	11 9	1[illegible] 0	12 0	6	0	0	0
	10	14 6	14[illegible]	14 8	14 8	1 2	0	0	0
	20	54 0	62 9	63 8	64 3	14 9	12 8	12 3	1[illegible] 3
	30	9[illegible]	99 2	101 0	102 0	18 7	14 5	14 5	13 4
19	10	8 8	30 3	30 9	—	2 0	0	0	0
	20	94 8	103 3	105 7	107 5	17 7	4 8	0	0
	30	146 0	18[illegible] 4	[illegible]10 3	3[illegible] 3	90 0	64 0	60 1	58 3

[1] Deformation units are in micra and are the difference between a recorded value and original length

both graphically (Figure 23) and numerically via the voltmeter printing readout If a specimen returned to original length the test was deemed complete If the specimen did not return to original length recordings were continued for 30 after unloading Ten minutes were permitted between tests

The results summarized in Table 11 and illustrated in Figure 23 were as follows Under the constant load of 5 kg 2 specimens attained maximal deformation almost immediately after application of the load with no increase noted for the remainder of the test period Upon release of the load they returned to original length with most of the recovery being attained at the first instant of unloading and the remainder within a few minutes

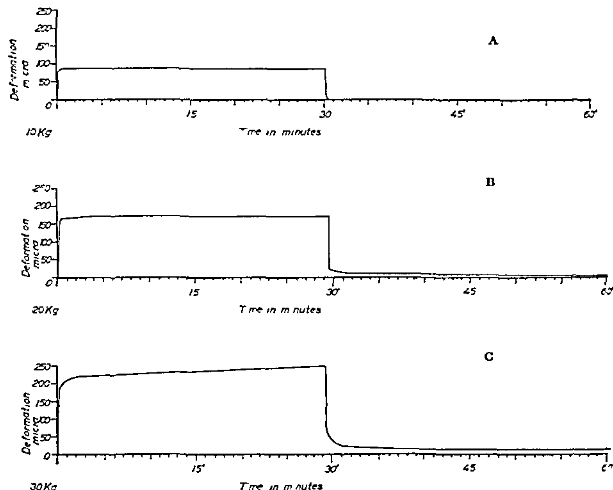


Figure 23 Changes in deformation over time under differing constant loads in one specimen A The behavior with a 10 Kg load It is seen that the final deformation is attained quickly and when the load is released at 30 complete recovery takes place B A 20 Kg load There is a definite delay in the attainment of a constant deformation When the load was released at 30 the specimen did not regain its initial length C A 30 Kg load has been applied The specimen continued to deform for the entire 30′ load period When the load was released after 30 permanent deformation is seen This deformation was superimposed upon that from the B test since the machine was rezeroed after test B

With a load of 10 kg the qualitative behavior began to vary A definite retardation in attainment of total deformation occurred in some of the specimens At this load four specimens regained original length and one did not

With the load of 20 kg additional changes were seen All specimens showed progressive deformation up to 30 With removal of the load only one specimen regained original length within 30

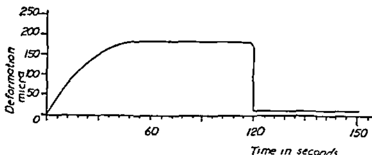


Figure 24 A rapidly recorded strain time test A 30 Kg load was applied and maintained for 2 and released It can be seen that there was delayed elasti ity when the specimen was loaded at O and instantaneous elasticity plus delayed elasticity when the specimen was unloaded The difference in slope is due to a difference in the speed of loading and unloading as explained in the text

The changes with the 30 kg load were similar to those of 20 kg but more pronounced in that deformation was greater and none of the specimens returned to original length within 30

The following features were common to all tests The initial deformation was attained as rapidly as the specimens could be loaded (10—15) with the equipment used while the initial recovery length was attained as rapidly as they could be unloaded (1—2) From this it would appear reasonable to conclude that bone possesses the feature of instantaneous elasticity in addition to retarded elasticity However the feature of instantaneous elas ticity cannot be immediately deduced from the curves in Figure 23 for the curve shape in constant recording apparatus is a function of recorder speed The presence of this phenomenon was confirmed in additional tests on differ ent samples from these subjects utilizing rapid recorder speeds and short term testing (Figure 24)

It was apparent that bone under certain constant loads will gradually yield and when a greater load is applied greater yield is to be expected This feature varies from subject to subject Analysis of the strain time curves for all subjects showed the following equations to fit the data best

$$\epsilon = A(1 - e^{-Bt}) \text{ for loading where}$$

A = a constant determining the ultimate deformation that will be attained and B = a constant determining the rate at which this deformation is reached

$$\epsilon(t) = \epsilon + \epsilon_0 e^{-Bt} \quad \text{for unloading where}$$

ϵ = some final deformation
ϵ_0 = deformation that remains after the instantaneous component of recovery
B = a constant for the rate of decrease in deformation

TABLE 12 *Deformation and Recovery from a Twenty four Hour Constant Load*[1]

Subject	Initial Deformation	Loaded						Initial Recovery	Unloaded					
		Time in Hours							Time in Hours					
		1	5	10	15	20	24		1	5	10	15	20	24
1	109 0	137 7	143 9	144 4	146 3	147 1	147 1	[2]						
2	103 9	135 1	157 5	171 6	178 5	184 8	190 6	61 1	29 3	20 8	16 6	15 2	13 9	11 9
3	113 8	178 1	187 6	194 7	203 0	205 3	199 3	83 0	59 4	54 3	52 3	51 6	50 0	49 0
7	103 6	128 9	140 7	142 1	143 7	144 [illegible]	144 2	37 8	18 2	15 0	12 9	12 5	11 3	11 [illegible]
10	198 8	341 9		Fracture										

[1] Deformation is recorded in microns In the unloaded half of the table the deformations are to be interpreted as the remaining deformation at the time cited

[2] This test had to be discontinued at this time to permit electrical work in other parts of the laboratory

Yet it could not definitely be stated on the basis of these data that the final deformation under the higher loads would be approached asymptotically as the loading equation implies or that the deformation resulting from the higher loads would not eventually be recovered Longer term tests were required

Part 3

Five additional specimens from the same subjects as in part 2 were used The test set up and specimen size were the same A 30 kg load was applied and maintained for 24 hours then released The recovery period was recorded for an additional 24 hours

Results of these longer term constant load tests at selected times are presented in Table 12 Two specimens attained a constant deformation within 24 hours two continued to deform for the entire period and one specimen failed after one hour In the three specimens in which a recording of unloading was obtained all showed persistent deformation at the end of the 24 hour recovery period The data from the 2 specimens that showed continuing deformation for the 24 hour load period indicated that a constant deformation would be reached in the future In the recovery recordings it was seen that some further decrease in deformation would have taken place but that original length would not be regained

It can be concluded from this phase of the experiment that bone will attain a constant deformation under a constant load or will fail If the load is of sufficient magnitude permanent deformation will result

Analysis

With the experimental evidence presented the steps by which the mechanical model for bone was developed can be undertaken This was done in stages First load deformation curves of tests reported in Chapter III were analyzed with a view toward a mechanical model The second step consisted of review of the specific experiments Next a model was postulated that was compatible with all of the information at hand The chief goal was to obtain the simplest model that could account for all of the behavior observed

Inspection of all load deformation curves in the test specimens revealed one common feature for all axes of loading rates of loading stages of hydration etc *There were no straight lines* (Figure 25) Granted that in certain instances the deviation from linearity was not great the basic fact is unchanged This feature eliminated the perfectly elastic body In addition the fact that there was a progressive increase in stress until failure of the specimens eliminated the perfect plastic and rigid plastic bodies from consideration A simple Newtonian liquid did not have to be considered The elimination of these fundamental bodies was implicit from the start but it was necessary to consider them since for example the Hookean body could have represented a close approximation of a working model

That elastic behavior is a feature of bone was evident from the cycle and creep studies — most of the attained deformation was recovered

The presence of viscous damping of some type in bone could be deduced from several features — 1) the fact that deformation up to some constant load is some function of the deformation rate 2) the fact that total deformation under a constant stress was not attained instantaneously i e bone has a retardation time 3) the fact that bone has a relaxation time 4) the fact

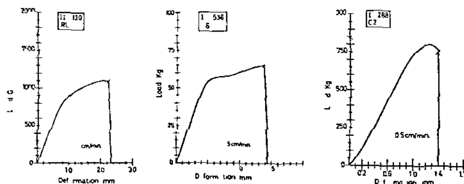


Figure 25 Typical load-deformation diagrams to failure Left — Bending end supports center load Center — Tension. Right — Compression of a 5 × 10 × 15 mm block. The rate of deformation (d) is stated with each curve Complete failure is indicated by F

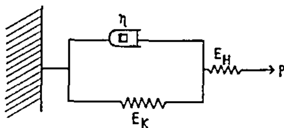


Figure 26 A possible rheologic model for cortical bone It is shown as a Hooke element combined with a Kelvin element This behavior could also be represented by an Hooke element in parallel with a Maxwell element

that an hysteresis loop was present on load unload cycle testing Also the shape of the usual load deformation curve although not conclusive in and of itself is strongly suggestive

The Kelvin and Maxwell bodies were then reconsidered since they are the simplest bodies containing both an elastic and viscous element The Kelvin body has a retardation time in common with bone However it does not have a relaxation time From eq 4 put $\epsilon=\text{constant}=\epsilon_0$ then $d\epsilon/dt=0$ and

$$\sigma=E\epsilon_0$$

The Maxwell body possesses the feature of instantaneous elasticity and a relaxation time in common with bone However under a constant stress deformation continues to increase whereas the constant load experiments showed that deformation became constant In addition it was shown in eq 9 that with a constant deformation stress relaxes to zero rather than to a new lower level as demonstrated in the stress relaxation studies

At this stage it was necessary to postulate a working model to account for some of the discrepancies noted and to attempt to fit this model to the data A model that appeared to account for the behavior at smaller loads is shown in Figure 26 It consists of a Hooke body linked in series to a Kelvin body Introduce the subscripts $_H$ and $_K$ to denote Hookean or Kelvin behavior The relation between stress and strain in this model is governed by the following equation

$$\frac{d\sigma}{dt}+a\sigma=b\frac{d\epsilon}{dt}+c\epsilon \tag{10}$$

where

$$a=\frac{1}{\eta}(E_H+E_K) \quad b=E_H \quad c=\frac{1}{\eta}E_HE_K$$

Eq (10) is the constitutional equation of the model

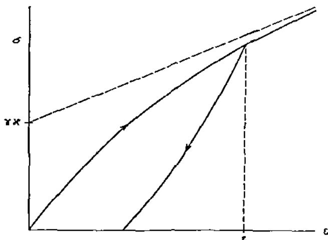


Figure 27 Diagram to demonstrate the behavior of the model Figure 26 at a constant rate of deformation and unloading from a certain deformation

First it was necessary to analyze this model in relation to the experiments cited Consider the case of loading and unloading with a constant rate of deformation The time derivative $d\epsilon/dt$ is now constant say ν and stress becomes a function of strain Eq 10 yields the solution

$$\sigma=\gamma\nu\left(1-e^{-\frac{a}{\nu}\epsilon}\right)+\frac{c}{a}\epsilon \tag{11}$$

where

$$\gamma=\frac{ab-c}{a}$$

Eq (11) thus shows the relation between σ and ϵ for this case and from Fig 27 it is seen that the $\sigma-\epsilon$ curve approaches a straight line asymptotically the slope of which is c/a or $E_K E_H/E_K+E_H$ This was in agreement with the experiments

Now consider the case of unloading from a certain deformation in Figure 27 at a rate of deformation $d\epsilon/dt=-\nu$ From equation (10) the following solution is obtained

$$\sigma=\gamma\nu\left[\left(2-e^{-\frac{a}{\varkappa}\epsilon}\right)e^{-\frac{a}{\varkappa}(\epsilon_1-\epsilon)}-1\right]+\frac{c}{a}\epsilon \tag{12}$$

Eq (12) satisfies the down curve of Figure 27 and the model therefore satisfied this behavioral feature of bone

Next the model was considered in relation to the data showing that the deformation of specimens decreased with a more rapid rate of loading and that

so the strain (σ_0/E_K) which would occur instantaneously without the dash pot is approached exponentially. The following is thus obtained

$$\epsilon = \frac{\sigma_0}{E_H} + \left(\frac{\sigma_0}{F_K}\right)\left\{1 - e^{-\frac{F_K t}{\eta}}\right\} \quad (18)$$

so that the strain (σ_0/E_H) is attained instantaneously and final strain asymptotically approaches the level $\sigma_0/F_K + \sigma_0/E_H$. This predicted response for the model agreed with that derived from the data on page 59. If as in the creep studies the σ_0 is continued until deformation ϵ_0 is attained and then released quickly, the strain at time t will be composed of two components as above, that in the Hooke body which is recovered instantaneously, and that which is recovered exponentially according to

$$\epsilon_K = \left(\epsilon_0 - \frac{\sigma_0}{E_H}\right)^{-\frac{F_K t}{\eta}} \quad (19)$$

Therefore the deformation will ultimately be recovered.

However, it was seen in the creep studies that at 30 kg loads none of the specimens regained original length after release of the load. The model postulated for lower loads did not permit explanation of this feature and therefore an additional mechanism had to be added to account for this. Since deformations tended to become constant with all of the loads in the creep studies, this was evidence against the inclusion of an additional viscous damper in series. Additional evidence against a viscous damper in series was cited earlier — at low loads all deformation was recovered.

Therefore it was logical that the residual deformation was due to plastic flow and that a plastic friction element had to be added in series. It was necessary to include multiple friction elements in series since many of the stress-strain diagrams in the study showed a definite increasing load requirement to produce failure after a region of plastic flow (Figure 25 B). This type of behavior can be represented in a mechanical model by a series of frictional contacts loosely connected by strings (*Jaeger* 1956). If these are appended to the model, Figure 29 is the result. The series of friction

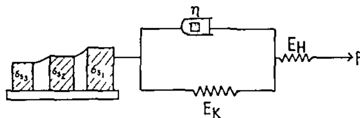


Figure 29. The working model. Figure 26 has been modified to include three frictional elements σ_{s_1}, σ_{s_2}, σ_{s_3} loosely connected by strings to account for plastic flow and work hardening.

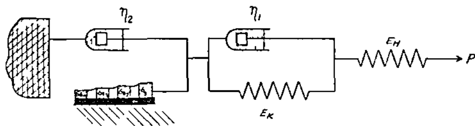


Figure 30 A further modification of the working mod l that accounts for damping of plastic flow

contacts each of which has a progressively smaller yield stress can be under stood as acting in the following fashion The force which is acting on the bone produces no permanent deformation until the yield stress of the first frictional contact is reached If the force is then maintained at this level the flow of the first frictional contact is limited by the yield stress of the second friction element which will not deform until yield stress of the com bined friction elements is reached This continues in a stepwise fashion as the force increases It is to be understood that the number of friction ele ments to be included has not been determined thus Figure 29 is illustrative

The appendage of the series of friction elements accounted for all of the data with one exception In the creep studies it was noted that there were no sudden increases in deformation after the initial load was applied i e the deformation increased gradually until a constant level was reached If the friction elements were acting in an undamped fashion then one would expect to see sudden increases at various phases of the strain time diagrams as different yield stresses were overcome with the resumption of increasing deformation as the Hooke Kelvin element continued to deform It was there fore nece sary to damp the action of the friction elements This can be done by adding another viscous damper in parallel (Figure 30) The addition of this element thus prevents the friction elements from deforming in tan taneously Conversely the deformation of the damper is limited by the yield stresses of the friction elements There was however no evidence to support the addition of a second viscous damper In view of this the model was re arranged so that the first vi cous damper affected the spring and friction elements (Figure 31) This model will act in the following fa hion as long as the stress in the spring E_K is less than stress in the first friction element σ then eq (10) is valid Above σ the model behaves as a Maxwell body as the level $\sigma + \sigma_s$ is approached If the stress does not attain $\sigma + \sigma$ deforma tion will become constant This is repeated as successive yield stresses are encountered

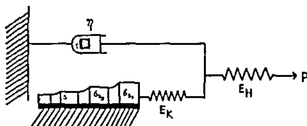


Figure 31 A Rheological Model for Cortical Bone This is a *generic* model A description is in the text The constants for the springs are maintained E_H E_K as in previous models since there is Kelvin behavior below the yield stress of the friction element σ_s

This model (Figure 31) thus explains all of the observations and answers the requirement of being the simplest model that was compatible with the available data It consists of a Hooke body linked in series to a unit consisting of a Newton body in parallel with a modified Prandtl body No attempt should be made to ascribe specific anatomical elements to the components of the model

Recapitulation

The model developed here describes general mechanisms by which bone samples deform *in vitro* It accounts for the properties of instantaneous elasticity retardation time relaxation time plastic flow and damped plastic flow, all having been observed in samples tested in this study It can serve as a basis for the quantitative prediction of cortical bone properties

The model provides a partial explanation for differences in physical properties that are noted when different conditions of testing are used such as the effects of drying temperature and changing the rate of deformation

A stress strain diagram of dry tested bone is more nearly linear than that of wet tested bone Stress relaxation and hysteresis are decreased when bone is dry In terms of the model this is equivalent to stating that bone is more elastic when dry than wet The effects of the viscous damping are vitiated by the drying leaving in the model a spring in series with friction elements or a perfectly plastic body Under a progressive load at a constant rate of deformation the expected behavior is that of dry bone tested to failure

It was shown that increases in deformation were present when samples were tested at 37 C as contrasted to 21 C This temperature dependent behavior is expected in substances possessing viscous properties and is therefore expected behavior in bone in view of the presence of a viscous damper in the model

The amount of deformation in a sample varied with the rate of deformation the samples deforming less at a more rapid rate of deformation than with a slower rate In addition deformation varied with the duration of stress and stress varied with the rate of deformation. It was predicted that stress should vary with the rate of stress There are many possible combinations of these variables all of which would result in differences between calculated properties

In the derivation of the model previously undisclosed facets of the physical properties of bone were delineated Other features were confirmed Essentially this work has demonstrated that it is possible to describe the behavior of bone in terms of a mathematical model With this as a matrix a different approach to the study of the physical properties of bone can be undertaken Heretofore the ultimate strength and modulus of elasticity have been the most frequently studied properties of bone The properties of stress relaxation strain retardation instantaneous elasticity and yield stresses have received relatively

little attention It was shown that the modulus of elasticity is not constant Similarly it is possible that the ultimate strength of bone may change with the rate of deformation (*McElhaney* 1965) rate of stress and other potential variables The same would apply to the other properties just mentioned Therefore it becomes apparent that rigid standards of testing are needed for the comparison of data from different sources and for the incorporation of the study of the physical properties of bone into the realm of medical diagnosis

In this study the constants for elasticity viscous damping and yield stresses were not derived since it was felt that they should be based upon mean values obtained from a large group of normal subjects With the determination of the model constants it will be possible to predict the reaction of bone to mechanical forces under conditions otherwise difficult or impossible to simulate in a laboratory For the purpose of prediction it would be better to devise an electrical analogue for the mechanical model shown here The appropriate electrical equivalents exist (*Stacy* 1955 *Papazian* 1962) and their use facilitates the confirmation or prediction of experimental results (*Stulen* 1962) and would support further investigations of this type

SUMMARY

A study of the physical properties of bone utilizing 663 samples of human moral cortex obtained at autopsy from 43 subjects has been performed he study was conducted under controlled laboratory conditions in which e effects of variables in the method of preparation methods of storage ethods of testing ages of subjects sources of samples and their microatomy were examined From this information it was possible to derive r the first time a model for the deformation of cortical bone using rheologic mbology and methodology

CONCLUSIONS

In the studies related to the effects of variables in the selection preparation storage and testing methods the following features presented in more detail on page 43 were demonstrated

a Freezing of samples has no effect on the physical properties of cortical bone Alcohol and formaldehyde fixation may have some effects

b Air drying changes the properties

c Heating to 100—105 C produces marked changes in the properties

d The permanent effects of heating when combined with drying are greater than with either variable alone

e The deformation of wet samples varies directly with the temperature of testing

f Wet samples can be loaded repetitively without permanent effects if small loads are used

g There are significant differences in physical properties from subject to subject and within various locations in the femur No differences could be attributed to age or Haversian canal volume

The following properties were found to be present in cortical bone

a Instantaneous elasticity

b Strain retardation

c Stress relaxation

d Multiple yield stresses

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Errata

Page 43 line 5a Sentence should be read
Decrease the ultimate fiber stress

Page 60 Table 12 Subject 3 The values should be read
199 3 at 15 hours 203 0 at 20 hours and 205 3 at 24 hours

Page 65 Eq (17)
A minus sign is omitted before the exponent

Equations (6) (17) (19) and those on page 59
t exponents should be read $t-t_0$

Figure 19 B Ordinate should be read $\frac{\sigma_0}{E}$ rather than σ_0

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WALTER EDGREN

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COXA PLANA

A CLINICAL AND RADIOLOGICAL INVESTIGATION WITH PARTICULAR REFERENCE TO THE IMPORTANCE OF THE METAPHYSEAL CHANGES FOR THE FINAL SHAPE OF THE PROXIMAL PART OF THE FEMUR

Translated by Eva Palmgren

To my Family

CONTENTS

ACKNOWLEDGEMENTS

I should like to express my gratitude to my friend and former teacher Professor C Gösta Jansson M D who directed my interest to the radiology of skeletal diseases

The present study was started in 1955 At this time a relatively large number of patients with coxa plana had been registered at the Radiological Department of the Orthopaedic Hospital of the Invalid Foundation and some primary results of healing could be evaluated I am deeply grateful to the late Professor Fabian Langenskiöld M D the former Head of the Hospital for his initiative and valuable guidance in the early stage of the work

Since the autumn of 1956 my work has been followed with interest and encouragement by my present chief Professor Anders Langenskiöld M D In the evaluation of the various aspects of the radiological course in coxa plana I have thus had the advantage of profiting by Professor Langenskiöld s extensive knowledge on the normal and pathological mechanisms of bone growth He also revised my manuscript with constructive criticism For all this generous aid I wish to extend my warm thanks

My thanks are due to my colleagues at the Orthopaedic Hospital of the Invalid Foundation who helped me with the radiological examinations and examined the patients clinically

I am also indebted to the nurses and the technical staff of the Radiological Department Their help in the radiological examinations and in assorting the material of radiographs was very valuable

Furthermore I wish to thank the staff at the Hospital Reception who provided me with the hospital records and to the photographer of the Hospital Miss L Mikkola who copied the radiographs for this study

Mrs Eva Palmgren Ph M translated my thesis into English and helped me in preparing the English manuscript I thank her for good cooperation I am also indebted to Mr Kingsley Hart M A who revised the translation

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Helsinki March 1965 Walter Edgren

I INTRODUCTION

Among the so called aseptic necroses coxa plana occupies a central position owing to the relatively frequent occurrence of the disease and owing to the fact that its location to the hip joint which is of such great significance to the mobility of human beings makes it a serious clinical and social problem

The denomination coxa plana introduced by H WALDENSTRÖM in 1920 describes the deformity — a flattening of the femoral head — caused by the disease

In the extensive literature concerning the radiological course in coxa plana interest has mainly been focussed on the changes of the femoral epiphysis and the ultimate shape of the latter after the completion of healing In spite of the great importance of the metaphysis and the greater trochanter for the modelling of the proximal end of the femur and although the trochanter in addition influences the statics of the hip joint less attention has been directed to the changes in these structures

On inspection of serial radiographs of patients with coxa plana I observed that end results which were satisfactory from the standpoint of the shape of the femoral head were sometimes markedly impaired because the greater trochanter was abnormally large in relation to the head and neck of the femur In certain cases the tip of the trochanter extended by several millimetres over the proximal surface of the femoral head

It seemed a reasonable assumption that this secondary deformity was due to premature closure of the subcapital growth line of the affected hip as compared with the subtrochanteric growth line in which growth sometimes continued for a long time after the vertical growth of the metaphysis had been arrested

Furthermore I observed that certain changes of the metaphysis almost constantly occurred on the radiographs of coxa plana patients These changes *i e* irregularities of the proximal surface of the metaphysis were all of the same type but varied in degree from case to case They were often marked in

III. REVIEW OF THE LITERATURE

CLINICAL AND RADIOLOGICAL INVESTIGATIONS

Till late in the nineteenth century the understanding of juvenile diseases of the hip was limited to congenital luxation and coxitis. From the latter heterogeneous group disorders of a non-inflammatory nature were, however, distinguished even before the introduction of radiological methods of investigation. In 1881 FIORANI described a typical deformity of the proximal end of the femur which HOFMEISTER in 1894 gave the name of coxa vara. In 1897 MAYDL described two cases of arthritis deformans in adolescents. During the next few years a large number of reports on arthritis or osteoarthritis deformans coxae juvenalis were published. Those of HOFFA (1901), v. BRUNN (1903), NEGRONI (1905), PREISER (1907), FRANGENHEIM (1909) and BIBERGEIL (1910) may be mentioned in this connexion because the descriptions and the illustrations suggest that some of these cases probably were coxa plana.

In 1909 SOURDAT published a study on diseases of the hip joint. From a large material he was able to distinguish 8 cases showing typical clinical symptoms and radiological signs. These cases by SOURDAT listed as coxa vara seem to have been coxa plana, as judged on the basis of the description and the drawings.

In the same year (1909) H. WALDENSTRÖM described a disease which he called »der obere tuberculose Collumherd». On the basis of 10 cases he summarized certain *clinical and radiological features which still apply* in the main to coxa plana. Owing to the fact that all these patients responded positively to tuberculin WALDENSTRÖM regarded the disease as tuberculous in nature. The next year (1910) WALDENSTRÖM described the disorder in greater detail. He still regarded it as tuberculous but he concluded: »Der obere Collumherd ist also eine so charakteristische Erkrankung, dass sie eine selbständige Gruppe der tuberculosen Coxitiden bilden kann».

In 1910 the American LEGG, the Frenchman CALVÉ and the German PERTHES independently of each other described a non-tuberculous disease

of the hip in children which they had detected and studied during the preceding years Both the clinical picture and the radiological course of the disease were similar in the three reports and typical of coxa plana Thus the disorder may be said to have been definitely recognized as a separate clinical entity

LEGG s first paper called »An obscure affection of the hip joint« was based on 5 cases with signs of a disease which he found was not typical of any condition previously described He gave the following list of characteristic symptoms age 5 to 8 years a history of injury limping absence of pain absence of constitutional symptoms little or no spasm absence of shortening of the limb The radiological changes consisted of flattening of the femoral head an irregular translucent area near the epiphyseal line shortening and thickening of the femoral neck

Under the name of »Pseudocoxalgie« CALVÉ described 10 cases of a disorder of the hip which he could not refer to tuberculous coxitis or any other disease of the hip previously known The most typical clinical and radiological symptoms recorded were age 3½ to 10 years chronic or subacute joint symptoms with pain a limp and reduced mobility of short duration and signs of rickets The radiographs exhibited flattening of the epiphysis with two or more ossific centres hypertrophy of the neck of the femur coxa vara in some cases intact joint cartilage The cases healed with preserved mobility

PERTHES first report included 6 cases of the disease which he called »arthritis deformans juvenilis« He too emphasized the occurrence of a limp with or without joint pain and limitation of mobility as the main clinical symptoms As the first radiological sign discernible he mentioned flattening of the femoral epiphysis and subsequent deformation frequently cone shaped

In 1913 PERTHES published a second investigation »Ueber Osteochondritis deformans juvenilis« in which 15 new cases were described in addition to the 6 earlier ones He characterized the disease as »ein durch subchondrale Destruktionsherde bedingter im Laufe von Jahren sich vollziehender eigenartiger Schwund der oberen Femurepiphyse« The clinical and radiological pictures tallied with his previous observations PERTHES discussed WALDENSTRÖM S (1909 1910) reports and stated that according to his opinion the »upper tuberculous focus in the collum« described by the latter was osteochondritis deformans juvenilis

The above mentioned first reports were followed by a copious number of papers in which various aspects of coxa plana were discussed A large

proportion of these papers were short case reports Among the more important articles those of LEVY (1911) SCHWARZ (1914) DREHMANN (1914) BRANDES (1914) LEGG (1916) TAYLOR & FRIEDER (1916) and PHEMISTER (1921) may be mentioned On the basis of a case in which the focus in the femoral head was curetted the last mentioned author described the disease histologically as bone necrosis

In 1920 SUNDT published a monograph under the name of »Malum coxae Calve-Legg Perthes» in which various aspects of the disorder were discussed on the basis of 66 cases

WALDENSTRÖM in 1922 reported a series of 22 cases which he had followed from the onset till the completion of healing On the basis of his observations he presented his well known classification of the different stages of the disease

STRÅHLE, likewise in 1922 published a survey of the disease and reported his own observations on 5 cases

RIEDEL (1922 1923) and AXHAUSEN (1923) described the results of histological investigations

In a study on non tuberculous diseases of the hip FROELICH (1923) reported 7 cases of coxa plana

In 1924 a monograph by MOLLER based on clinical and radiological investigation of 74 cases was published

CAAN in 1924 published an extensive survey mainly based on previous reports by other investigators KIDNER (1926) and ROCKEMER (1927) described the results of histological studies which revealed necrosis without any signs of inflammation

In 1931 FERGUSON & HOWORTH reported observations made in connexion with arthrotomy and drilling of the femoral epiphysis in 21 patients In the early stage of the disease the synovial membrane was thickened soft and vascularized In addition villus formations oedamatous and thickened periosteum and normal joint cartilage were found The authors considered the changes to be suggestive of inflammation HOWORTH (1948) was [illegible] le to confirm his previous observations in connexion with 50 later op[illegible] ions HAYTHORN (1949) who examined the tissues removed from the e[illegible] s of pat[illegible] operated upon for coxa plana observed aseptic necros[illegible] [illegible] bone marrow [illegible]
(1949) re[illegible] [illegible] he results of a follow up inves[illegible] [illegible] n 153 coxa plan[illegible]
[illegible] ECK disc[illegible] pathogenesis of coxa plana [illegible] sed on 300 c[illegible] 1950 and 1951 a and b)

In 1953 JONSATER published a study based on 34 cases representing different stages of the disease investigated by needle biopsy and 40 cases examined by arthrography of the hip joint. JONSATER summarized his results as follows.

The disease reaches its climax during the initial stage which, roughly speaking, implies total necrosis of the epiphysis. Since haemorrhages do not occur, the necrosis is ischaemic by nature. In this stage the epiphysis is soft. The radiological fragmentation stage is histologically a reparative stage during which the dense areas on the radiographs correspond to necrotic bone and the translucent areas to ingrowing reparative tissue and fresh not yet fully mineralized bone. The epiphysis is harder than in the initial stage. The radiological reparative stage is also histologically a regenerative phase which differs only in degree from the fragmentation stage. The epiphysis is harder than in the fragmentation stage.

HELBO (1953) too published a monograph on coxa plana which was based on clinical and radiological investigation of 204 cases. Of these 66 were treated by protracted bed rest. They were compared with symptomatically treated or untreated cases. The end results in the first mentioned group were very good.

In 1954 GOFF's large monograph on Legg Calve Perthes syndrome was published in which heredity, constitutional aspects, growth phenomena and methods of treatment are discussed at length. The end results in 65 cases are reported.

In the same year PERTTILA reported the results of a follow up investigation of 33 cases seen from 10 to 20 years after the active phase of the disease.

In 1957 RYDER *et al* reported a series of 104 cases and KATZ described the end results in 100 cases.

EVANS in 1958 published the results of a follow up study of 48 cases of coxa plana.

WANSBROUGH *et al* (1959) reported their observations on a series of 129 cases and O'GARRA (1959) the results of 25 cases.

The most recent contributions to the clarification of the clinical and radiological aspects of the disease have been published by PONSETI & COTTON (1961), RALSTON (1961), BERGSTRAND & NORMAN (1961), GOFF (1962) and MOSS (1964).

Radiological evaluation of end results. EYRE BROOK (1936), SJOVALL (1943) and HEYMAN & HERNDON (1950) used various methods for the measurement of height, flattening and increase in breadth of the femoral head as compared

with the unaffected side The results were expressed as epiphyseal index epiphyseal quotient or comprehensive quotient

Regarding all these methods of measurement Goff (1954) emphasized the difficulty in defining the points of determination In addition he pointed out that they are of no use in bilateral cases as was also emphasized by Helbo (1953)

Goff evaluated the shape of the femoral head on direct inspection of the radiograms He classified the results as *spheroidal type mushroom type* and *irregular type* (*malum coxae juvenilis*) As an aid in determining the spherical outline of the head he used a protractor by scratching circles at 2 mm intervals on a piece of transparent acetate

Mose (1964) estimated the shape of the outline of the head in the same way as Goff and completed this estimate with calculation of the epiphyseal quotient as suggested by Sjovall *Good results* meant that the head was spherical the outlines in the frontal and lateral views constituting circles with identical radii and that the epiphyseal quotient was above 60 per cent *Fair results* implied that the head was spherical but crescent shaped and flattened with an epiphyseal quotient below 60 per cent *Poor results* comprised all those heads in which the radii of the outline circles differed in the lateral and frontal views and all heads which were not spherical irrespective of the quotient

AETIOLOGY AND PATHOGENESIS

The authors of the first reports on coxa plana differed in their opinions regarding the aetiology of the disease Waldenstrom considered it to be a mild form of tuberculosis Legg believed that it was due to trauma Calve who detected signs of rickets in some of his patients regarded the latter disorder as a possible cause of coxa plana Perthes suggested the possibility of an infectious aetiology

Trauma

Necrosis of the femoral head resembling coxa plana is relatively frequent after closed reduction of a congenitally luxated hip This has been emphasized by many authors as evidence of a traumatic aetiology of coxa plana (Eden 1912 Bibergeil 1912 Bade 1913 Brandes 1916 Legg 1916 Rehbein 1922 Howorth & Smith 1932 Lima Esteve & Trueta 1960 and others)

After traumatic luxation necrosis of the femoral head has been described by ELMSLIE (1919) REHBEIN (1923) NICOLAYSEN (1931) DYES (1935) BLUMENSAAT (1936) GOLDENBERG (1938) LINDEMANN (1957) ULLOA (1963) and others

In adolescents necrosis of the femoral head following fracture of the neck has been reported by a number of investigators e g AXHAUSEN (1922) REHBEIN (1923) JOHANSSON (1927) KRAFT (1931) LANGE (1932) BORNEBUSCH (1940) BRAILSFORD (1943) BERNBECK (1951 b) and RATLIFF (1962) These authors regarded their observations as evidence in favour of a traumatic aetiology

HELBO surveyed the cases previously reported in which trauma had been indicated as the cause Trauma was mentioned in a third of 258 case reports In the histories of 22 per cent of his own patients HELBO detected trauma of a kind that might have had a causal relationship with the onset of the disease He regarded trauma as a possible cause of coxa plana

Inflammatory causes

After WALDENSTROM and PERTHES many authors have suggested the possibility that coxa plana is due to inflammation DREHMANN (1914) PHEMISTER (1921) BERNBECK (1951 b) HOLLANDER (1952) and others have described conditions resembling coxa plana in connexion with inflammatory processes in the hip region in particular CALVE (1910) and SUNDT (1949) observed coxa plana in association with rheumatoid arthritis SINDING-LARSEN (1915) AXHAUSEN (1922) RIEDEL (1923) and HOWORTH (1948) described coxa plana in connexion with infections such as tonsillitis scarlatina and influenza JACOBS (1960) reported a study of 25 patients with synovitis in the hip joint In 3 of these the disease later developed into coxa plana He suggested a causal relationship between synovitis and osteochondrosis as a reasonable hypothesis

Hereditary and constitutional factors

A large number of authors have reported a familial occurrence of coxa plana e g CALVE SCHWARZ BRANDES (1920) SUNDT (1949) and MONTY (1962) STEPHENS & KERBY (1946) were able to trace coxa plana through five generations in the same family They found the disease in 28 out of 63 members investigated and regarded their results as indicative of inheritance according to Mendel s law

JEQUIER & FREDENHAGEN (1948) described a family in which coxa plana could be traced through seven generations In 14 cases the diagnosis was verified These authors regarded their observations as evidence of a dominant hereditary aetiology

Among 200 patients with coxa plana HELBO (1953) detected 3 5 per cent who had close relatives suffering from this disease On comparison of the frequency of coxa plana with the frequency of its familial occurrence he concluded that the difference was significant and that the large number of familial cases could not be due to chance

GOFF (1954) found a family history of coxa plana in 20 per cent of his 103 cases From his own investigation and the data available in the literature he drew the conclusion that coxa plana is a mostly recessive seldom dominant condition with varying penetrance

In a series comprising 129 cases WANSBROUGH *et al* (1959) noted a family history of coxa plana in 9 3 per cent These authors considered the disease to be of constitutional origin and believed that minor traumata and systemic infection may perhaps precipitate the onset

Coxa plana was observed in monozygotic twins by GOFF (1954) GIANNESTRAS (1954) SODERBERG (1957) WANSBROUGH (1959) DUNN (1960) and INGLIS (1960)

GOFF was able to demonstrate growth inhibition in his patients inhibition of the longitudinal growth of the lower extremities in particular Furthermore he observed delayed skeletal age in connexion with coxa plana

RALSTON (1961) reported that the bone age in his series was delayed by an average of 1 year and 9 months

MAU & SCHMITT (1960) suggested that constitutional dysostotic factors may be responsible for the development of coxa plana

Endocrine factors

Radiological changes of the hip joint resembling those seen in coxa plana were described in cretins by BIRCHER (1909) and LAWEN (1909) LOOSER (1929) regarded these changes as due to a retarded transformation of cartilage to bone ALBRIGHT (1938) reported favourable results with thyroid medication in similar cases

SUNDT (1920) suggested that the cause of coxa plana is osteodystrophy due to hereditary endocrine factors and that the onset of the disease is precipitated by trauma or infection

Thyroid function was studied by GILL (1943) in 20 children with coxa plana by KATZ (1955) in 32 children by CHAPMAN (1956) in 10 children and by BEILER & LOVE (1956) in 22 In none of these investigations was hypothyroidism observed

HOWORTH (1948) found that the basal metabolism was normal in patients with coxa plana

Nutritional factors

CALVE (1910) regarded rickets as a possible cause of coxa plana SUNDT (1920) reported that a third of his patients had a history of rickets GOFF (1954) tested patients with osteochondrosis for alkaline phosphatase and serum cholesterol without being able to detect any significant changes

SCHNEIDER (1937) demonstrated a decrease in vitamin A in children with coxa plana

BRAILSFORD (1948) stated that Legg Perthes disease is much more common among the poor than among the well to-do classes PEIĆ (1962) observed a relatively higher incidence of coxa plana among the children of manual workers By contrast GOFF (1954) detected no relation to economic levels or to housing or home environment

PONSETI (1956) suggested that the disease is due to changes in the chemical composition of the ground substance of the epiphyseal plate In biopsy specimens of the epiphyseal plate of patients with coxa plana and epiphysiolysis he observed changes resembling those seen in rats fed with a diet rich in aminonitrile WOROBEC & NORWOOD (1956) arrived at similar conclusions regarding the cause of coxa plana

Dysplasia of the acetabulum

BRANDES (1920) CALOT (1921) JANSEN (1923) and HILGENREINER (1933) attributed coxa plana to congenital changes of the hip joint In support of this view BRANDES described cases in which coxa plana developed in the unaffected hip in children with congenital luxation Later many authors (e g GUILDAL 1930 MORVILLE 1930 1935 WALDENSTROM 1934 SEVERIN 1942 HELBO 1953) have shown that coxa plana occurs in previously entirely normal hips

Racial factors

GOFF (1954) reported that coxa plana is rare in Negroes Indians and Polynesians

Circulatory factors

Many authors have suspected that disturbed circulation in the proximal end of the femur is the cause of coxa plana Mention may here be made of AXHAUSEN s (1922) theory concerning »bland mycotic embolism»

BERNBECK (1954) regarded coxa plana as osteonecrosis due to total infarction resulting from blockage of the epiphyseal vessels in the cartilage canals in the chondroepiphysis He presumed that trauma or infection may lead to degenerative cartilaginous oedema resulting in obstruction of the canals and arrest of the circulation and that the borderline lamella between the cartilage and the bone is then penetrated so that the acid cartilaginous fluid makes its way into the bone tissue and causes decalcification a chemical osteonecrosis

The investigations by TRUETA (1956 1957) regarding the supply of the proximal end of the femur are interesting in this connexion After injection of contrast medium into autopsy material and on the basis of sections and microradiographs he studied the circulation in 46 cases from the eighth foetal month to 17 years It emerged that the vessels in the ligamentum teres do not participate in the supply of the femoral head from birth until the age of 4 years and that the blood flow through the ligamentum teres is of no importance for the supply of the femoral head until the age of about 8 years After birth the metaphyseal vessels gradually decrease in size and at the age of 4 they are of practically no importance for the supply From the age of 4 to 8 years with individual variations the femoral head is exclusively supplied via the lateral epiphyseal vessels These are exposed to compression by the strong lateral rotator muscles and in extreme positions the limit of elasticity of the vessels may be exceeded TRUETA accepts trauma as a precipitating cause but emphasizes that the nutritional conditions in the femoral head at the coxa plana age are the primary cause of the disease As further evidence for this theory he points out that in a study on the vascular conditions in the proximal end of the femur in Negro children of the same age he found that the supply of the femoral head in this race occurs via the ligamentum teres earlier in life than in the white race This would explain the rare occurrence of the disease in Negro children

The investigations by ULLOA (1962) regarding the blood supply in the proximal end of the foetal femur confirms TRUETA s results

The most recent contribution to research on the circulation in the proximal end of the femur is a paper by HIPP (1962) who studied this problem on the basis of angiographies in a normal series and in different pathological condi-

tions In coxa plana he observed partial obstruction of the proximal nutrient vessels of the femoral head and relatively frequent obliteration of the ramus profundus of the medial circumflex femoral artery During the progressive stage of the disease in particular the blood flow in these vessels was retarded

EXPERIMENTAL INVESTIGATIONS

Experiments on animals have been performed in order to produce necrosis by blocking or dividing the vessels supplying the femoral epiphysis

ISELIN (1918) divided the ligamentum teres in young dogs without any necrosis resulting NUSSBAUM (1923) divided the ligamentum teres and the periosteum around the femoral neck in young dogs The experiments resulted in necrosis of the head of the femur BENTZON (1926) injected alcohol into the area surrounding the metaphysis in young rabbits and goats A condition which histologically resembled coxa plana BERGMANN (1927) and MILTNER & HU (1933) brought about necrosis of the femoral head in rabbits the former by removing and the latter by dividing the periosteum of the femoral neck and by dividing the ligamentum teres

LEMOINE (1957) induced necrosis of the head of the femur in rabbits by division of the ligamentum teres division of the nutrient vessels to the head and division of the anterior circumflex artery

ROKKANEN (1962) was able to produce necrosis of the femoral head in rabbits *e g* by tightly ligating the neck with steel wire and by dividing the ligamentum teres

A LANGENSKIÖLD *et al* (1962) studied the changes following experimental dislocation of the hip in young rabbits After closed reduction of such hips necrosis of the head and the neck of the femur was observed

NAGURA (1937) and NAGURA & KOSUGE (1938) induced changes resembling coxa plana in rabbits by local blunt trauma of the femoral head From his experimental results NAGURA drew the conclusion that an aseptic necrosis is always primarily due to a subchondral fracture

NORMAL GROWTH OF THE PROXIMAL END OF THE FEMUR

Ossification of the femur begins in the seventh foetal week with ossification of the diaphysis At birth or immediately after an ossific centre develops in the distal end of the bone In the proximal end of the femur the epiphyseal plate in the newborn child forms a coherent, crescentic line The medial portion of the epiphyseal plate is transformed into the subcapital

epiphyseal cartilage which forms the growth zone of the femoral neck. Initially the neck grows almost straight in the cranial direction but soon the lateral portion of the pre plate also develops into the epiphyseal cartilage of the greater trochanter. Growth and modelling of the proximal end of the femur from now on occurs by reciprocal action of these two separate growth zones (MORGAN & SOMERVILLE 1960). The first effect of growth in the area of the trochanter is a decrease of the valgus position and increased growth of the proximolateral part of the bone. In the subcapital epiphysis an ossific centre develops in girls at the age of three to four months and

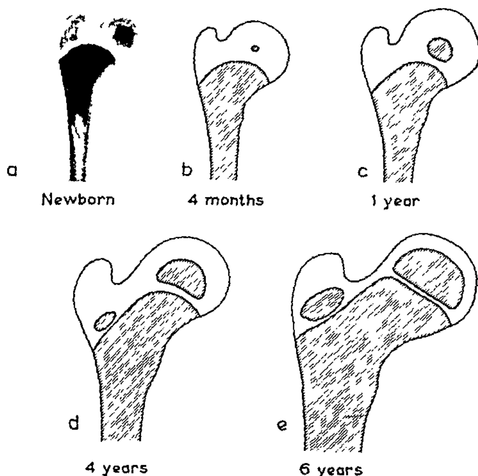


Fig. 1 The transformation of the preplate to separate growth zones for the femoral head and the greater trochanter. The development of the epiphyseal nuclei in the proximal end of the femur. *a* radiogram of the proximal end of the femur of a still born foetus (female) weighing 3250 g. *b—e* drawings made on the basis of radiograms.

in boys at the age of five to six months In the greater trochanter an ossific centre develops at the age of about four years (SCHMID & HALDEN 1949)

Fig 1 demonstrates the transformation of the pre plate its division into two separate epiphyseal plates and the development of the ossific centres in the femoral head and the greater trochanter

At the Orthopaedic Hospital of the Invalid Foundation investigations by the tetracycline method are in process regarding the growth of the proximal end of the femur in pigs These studies have shown that the growth of the greater trochanter occurs in equal parts in the metaphysis and by apposi-

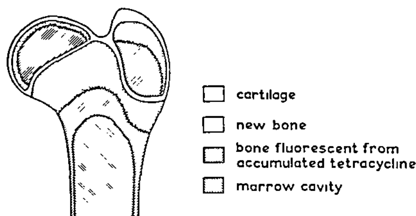


Fig Drawing of a frontal section through the upper end of the femur of a 14 week old pig injected eight weeks previously with tetracycline (50 mg/kg)

tion around the tip of the greater trochanter The growth of the femoral neck occurs in the metaphysis and is markedly stronger than the growth of the subtrochanteric region By contrast apposition is markedly weaker in the capital epiphysis than in the greater trochanter (A LANGENSKIOLD & SALENIUS unpublished observations) (See Fig 2)

TREATMENT

Previously the treatment of active coxa plana consisted in purely symptomatic measures immobilization and/or weight relief by bed rest by traction or by the use of plaster casts for some period of time (SCHWARZ 1914 BRANDES 1920 and others) Some authors *e g* PERTHES (1913) CALVE

(1910) and NIEBER (1916) preferred early mobilization CAAN (1921) and SUNDT (1949) maintained that the course of the disease and the end results could not be influenced to any appreciable degree by any kind of treatment

Later the importance of protracted non weight bearing has been generally accepted but owing to the long duration of the disease adequate accomplishment of such treatment meets with considerable difficulties Practical and social viewpoints have therefore determined the principles on which it is carried out

WALDENSTRÖM (1923) introduced a compromise therapy bed rest and traction only in cases where pain and contracture were present otherwise weight relief by crutches or splints Different modifications of this treatment have been used by SEVLRIN (1942) LEVY & GIRARD (1942) MINDELL & SHERMAN (1951) EVANS *et al* (1958) WANSBROUGH *et al* (1959) *and others*

BRAILSFORD (1932 cited by BRAILSFORD 1948) and DANFORTH (1934) reported good results after prolonged bed rest This method in combination with different kinds of traction and continued by weight relief accomplished with crutches or splints has later been employed by a large number of authors *e g* EYRE-BROOK (1937) GILL (1940) SJÖWALL (1943) HERNDON & HEYMAN (1952) HELBO (1953) GOFF (1954) RATLIFF (1956) RYDER *et al* (1957) O GARRA (1959) HOWORTH (1959) JACOBS (1960) RALSTON (1961) and MOSE (1964)

Duration of treatment Since DANFORTH in 1934 recommended non weight bearing for three to four years views have changed somewhat on this point Many modern authors regard one and a half to two years weight relief as adequate HAUGE (1956) treated his patients by non weight bearing for one year but after comparison with the end results in series treated in the same way for longer periods he recommended weight relief for one and a half years In his first study (1954) GOFF reported that the mean non-weight-bearing period in his series had been 27 months but later (1959) he reduced this time to nine months combined with crutch walking for further six months EVANS (1958) used an average of 25 months non weight-bearing

Regarding the treatment of bilateral cases the majority of authors — even those who prefer ambulatory treatment in unilateral cases — consider hospitalization to be the only possible alternative Bed rest is continued until either hip is trusted to tolerate weight bearing and then the patient is allowed to walk with the worse side in a caliper (MINDELL & SHERMAN 1951 WANSBROUGH *et al* 1959 and others) MCKENDRY *et al* (1960) described a brace for the treatment of bilateral cases of coxa plana which they had used

successfully GRIPENBERG & WALLGREN (1963) reported good results with Thomas splints in bilateral coxa plana

Previously operative treatment was only resorted to in poorly healed cases in part as a remodelling measure in part in the form of resection of the femoral head or osteotomy for the correction of malposition (CAAN 1924)

FREUND (1922) described 3 cases of severe deformation after coxa plana with positive Trendelenburg signs in which he successfully excised the joint capsule ventrolaterally removed osteophytes by chiselling and shifted the greater trochanter a couple of centimetres in the distal direction

In more recent years various procedures have been employed in order to damage the necrotic epiphysis and thus bring about its revascularization and more rapid healing BOZSAN (1932) FERGUSON & HOWORTH (1934) v ABERLE HORSTENEGG (1941) HOWORTH (1948) DUBOIS (1951) and KIENZLE (1953) used drilling of the epiphysis through the greater trochanter or the femoral neck Drilling and grafting were used by HACKENBROCH (1941) STUPNICKI (1952) BERTRAND (1954) CAMARGO (1957) and YAMAGUCHI (1959) BERNBECK (1948) and GARDEMIN (1951) evacuated the necrotic portion of the epiphysis CATHRO & KIRKALDY WILLIS (1963) plugged the evacuated epiphysis with spongy bone from the femoral neck or the crista iliaca and PITZEN (1951) PETER (1955) and SALVO LECARRE (1957) drove a metal nail into the epiphysis through the greater trochanter and the femoral neck

Subtrochanteric osteotomy was employed by SOEUR & DE RACKER (1952) and SLAVIK (1956) in order to alter the weight bearing surface of the epiphysis

With regard to medication accelerated healing with thyroid preparations has been reported by EDBERG (1918) MOLLER (1921) CAVANAUGH *et al* (1936) EMERICK *et al* (1954) FIELDS (1959) and others while PONSETI & COTTON (1961) observed no effect of thyroid medication

GOFF (1954 1959) used aureomycin and achromycin in coxa plana in order to promote growth

Androgenous and oestrogenous hormones in combination with thyroid preparations were administered by GLERITER *et al* (1959) KOSKINEN (1959) who noted a significant effect of human growth hormone and thyrotropin on the healing of fractures in laboratory animals suggested the use of this treatment also in aseptic necroses KRISTENSEN (1963) recommended anabolic steroids in the treatment of coxa plana

IV MATERIAL AND METHODS

MATERIAL

The material consists of all cases of coxa plana registered at the Radiological Department of the Orthopaedic Hospital of the Invalid Foundation during the years 1946—1958 The total number of cases is 276 Fifty of these were bilateral and the total number of affected hips is thus 326 The series includes 22 patients who were adult at the time of their first visit In these cases the process had already reached its final stage The annual number of registrations is shown in Table 1

TABLE 1 — *Annual number of patients with coxa plana registered at the Orthopaedic Hospital of the Invalid Foundation during the years 1946—1958 (total 276)*

Year	No of cases	Adult at the first examination
1946	6	2
1947	3	—
1948	7	—
1949	23	5
1950	23	4
1951	32	2
1952	28	—
1953	21	2
1954	35	1
1955	28	3
1956	18	—
1957	23	2
1958	29	1
Total	276	22

Of the present cases 246 had been remitted to the Radiological Department from the Outpatient Department of the Orthopaedic Hospital and 30 from the private practices of the doctors on the hospital staff

The distribution of the cases geographically and according to residence and family environment is seen in Tables 2 3 and 4

The small number of cases registered during the first three years (Table 1) is accounted for by the exceptional conditions prevailing after the war when the work in this hospital mainly consisted of the care of the war wounded and the means of communication were deficient

Table 2 shows that the geographical distribution of the coxa plana pa-

TABLE 2 — *Geographical distribution of 274 cases of coxa plana compared with the distribution of the whole population in Finland in 19[illegible]*

Province	Coxa plana		Whole population
	No of cases		
Nyland (Uusimaa)	63	23 0	17 0
Åbo & Björneborg (Turku & Pori)	37	13 3	15 5
Åland (Ahvenanmaa)	1	0 4	0 5
Tavastehus (Hame)	41	15 0	13 5
Kymmene (Kymi)	24	8 8	8 0
St Michel (Mikkeli)	20	7 3	6 0
Kuopio	29	10 6	11 5
Vasa (Vaasa)	26	9 5	15 0
Uleåborg (Oulu)	21	7 7	9 0
Lappland (Lappi)	12	4 4	4 0
Total	274	100 0	100 0

tients corresponded fairly well with the distribution of the whole population over the different provinces of Finland A slight preponderance of patients from the provinces of Nyland and Tavastehus is accounted for by proximity to the capital The relatively smallest number of patients had been remitted

TABLE 3 — *Distribution of 274 cases of coxa plana according to residence compared with the corresponding distribution of the whole population in 1952*

Residence	Coxa plana		Whole population
	No of cases	%	
Towns and market towns	98	35 8	34 0
Rural districts	176	64 2	66 0
Total	274	100 0	100 0

TABLE 4 — *Distribution of 264 cases of coxa plana according to social background compared with the corresponding distribution of the whole population in 1950*

Father's occupation	No of cases	% of cases	Distribution of children in the whole population according to father's occupation %
Workers	127	48	43
Farmers	71	27	36
Clerical or non manual managerial/professional	66	25	21
Total	264	100	100

from the province of Vasa (9 5 per cent against 14 6 per cent) This is due to the fact that two specialists on orthopaedics were practicing in this province during a great part of the time the present series was collected

As is seen in Table 3 the present study did not reveal any difference in the frequency of coxa plana between the rural and urban populations

In this series no particular social group seemed to be especially affected with coxa plana (Table 4)

METHODS

Clinical examination

The patients remitted from the Outpatient Department were clinically examined there As a rule gait and Trendelenburg's sign mobility of the hip joints and the length of the lower extremities were recorded In addition the erythrocyte sedimentation rate was determined in many cases and in some the protein bound iodine in serum No other laboratory tests were regularly performed The data regarding these examinations were obtained from the records of the Outpatient Department which unfortunately in many cases were incomplete

The clinical data regarding the private patients were obtained from the respective doctors In some cases I examined the patients myself

When the material was collected in 1956 I found that no less than 148 patients had to be summoned to follow-up examinations The majority of these had visited the Outpatient Department but failed to attend at the follow up examinations In a minor proportion of cases the treatment had been regarded as finished Of the 148 patients 100 attended at follow up investigations during the years 1958—1961 In about 10 cases no contact could be established and the remainder failed to attend

Radiological examination

All patients were radiologically examined Among the earliest cases there are some in which radiographs were taken in only one projection and a few where only the affected hip was examined

On radiological examination of a chronic disease of the hip such as coxa plana which necessitates repeated check-ups it is of paramount importance that a standardized method is employed so that the results of one examination are comparable with those of the next Since 1946 a modification of the method suggested by KNUTSSON (1938) has been used in the radiological examination of the present patients as well as in other examinations of the hip performed in this Department As a rule both hips are simultaneously radiographed on the same film Frontal views are taken with the patient supine with the legs extended in 20 degrees inward rotation In this position the neck of the femur is parallel with the film broadly speaking since according to v LANZ (1950) the antetorsion angle of the femoral neck is about 20 degrees in the coxa plana age

Lateral views are also taken with the patient supine with about 25 degrees flexion and 50—60 degrees abduction of the femora which are supported with wedges of sponge plastic The knees are bent and the feet placed against each other in the median line A maximum of symmetry is aimed at If the pelvis is slanting owing to atrophy of the gluteal muscles this is corrected with cushions The central ray is focussed immediately above the symphysis The target — film distance is 110 cm

In cases with contracture of the hip joint in which limited abduction makes a simultaneous examination of the two hip joints impossible in the lateral projection these are separately studied By keeping the pelvis aslant the desired position is achieved

The radiographs obtained by this technique have proved satisfactory

During the period of non weight bearing treatment check up examinations were made at intervals of three to four months in some cases at shorter intervals In a large number of cases the intervals between the check ups were much longer owing to failure of the patient to attend at the time arranged During the last few years this drawback has been eliminated to a great extent thanks to the work done in our hospital by nurses specially trained in social care

The first follow up examination after the completion of non weight bearing treatment was made after four to six weeks Subsequently the intervals between the examinations were gradually prolonged to one and two years at the time of completed growth

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In order to facilitate assessment of the shape of the femoral head the plastic protractor seen in Fig 3 was used

With the protractor placed on the radiograph the fit of the femoral head in one of the circles was estimated If the head was spherical the length of the radius was measured In unilateral cases the same procedure was carried out on the unaffected side

Furthermore the length of the femoral neck and the breadth of the metaphysis were measured in both hips in unilateral cases

V CLINICAL AND RADIOLOGICAL OBSERV[illegible]

GENERAL CONSIDERATIONS

Sex distribution Table 5 shows the sex distribution in the present
The ratio males to females is 4 1

Table 5 — Sex distribution in 276 cases of coxa plana

	No of cases	%
Males	223	80 8
Females	53	19 2
Total	276	100 0

Affected side The distribution according to affected hip in this seri[es is]
shown in Table 6

Table 6 — Distribution according to affected side in 276 cases of coxa plana

Sides	Males		Females		Total	
	No of cases	%	No of cases	%	No of cases	
Right	84	37	21	40	105	38
Left	97	44	24	45	121	44
Both	42	19	8	15	50	18
Total	223	100 0	53	100 0	276	100 0

Body build The body build was subjectively assessed by inspection in 21[illegible]
cases The results are seen in Table 7

In the cases exhibiting obesity the sella turcica was radiologically exam
ined No pathological changes were observed

TABLE 7 — *Body build in 215 cases of coxa plana*

	No of cases	/
Normal	183	85 1
Slender	24	11 2
Stout	8	3 7

TABLE 8 — *Age at onset in 265 cases of coxa plana*

Age in years	Males	Females	Total	/
2— 3	6	6	12	4 5
4— 5	61	10	71	26 8
6— 7	82	22	104	39 3
8— 9	41	8	49	18 5
10—11	21	5	26	9 8
12—14	3	—	3	1 1
	214	51	265	100 0

Age at onset The patient s age at the time when the first symptom[illegible] — a limp and/or pain — were observed was regarded as the onset [illegible] could be established in 265 cases as shown in Table 8

The youngest patient was 2 *years and 8 months* and the olde[illegible] years old at the time of onset of the disease

It is noteworthy that the ratio males to females is 1 1 in the [illegible] age group The small number of cases does not allow of any [illegible] however

In 11 cases the age at onset could not be established

Duration of symptoms The duration of symptoms at the [illegible] gnosis was calculated from the onset If the diagnosis had [illegible] some other hospital and adequate treatment had been insti[illegible] of time was regarded as the limit of the duration of sympt[illegible] treatment had not been instituted elsewhere this period [illegible] to the time when the disease was diagnosed in our Hosp[illegible] the duration of symptoms in the present series

Twenty two ultimately healed cases are omitted from Ta[illegible] duration groups consist of neglected cases the major[illegible] very advanced stage of reconstruction when first ex[illegible] the table that treatment had been instituted within [illegible] onset of symptoms in less than half the cases

TABLE 9 — *Time from onset of symptoms to diagnosis in 254 cases of active coxa plana*

Duration of symptoms in months	No of cases	%
0— 1	39	15.4
2— 3	43	16.9
4— 5	28	11.0
6— 7	39	15.4
8—12	32	12.6
13—24	49	19.3
25—36	24	9.4
Total	254	100.0

Mean duration 9.6 months

Stage of the process at the time of diagnosis On the basis of the radiographic findings at the time of diagnosis the present series was divided into groups according to JONSATER's (1953) modification of WALDENSTRÖM's (1923) classification The distribution of the cases is shown in Table 10

TABLE 10 — *Distribution according to stage of the process at the time of diagnosis in the whole series*

Stage	No of hips in unilateral cases	No of hips in bilateral cases	Total no of hips	%
Initial	101	46	147	45.1
Fragmentation	75	35	110	33.7
Reparative	33	8	41	12.6
Definitive	17	11	28	8.6
Total	226	100	326	100.0

The group »definitive stage» includes 6 bilateral cases In one of these the outline of one femoral head showed defects which will probably disappear later This hip was included in the group »reparative stage» If the cases in the group »definitive stage» are omitted the cases diagnosed in the initial stage constitute only 48.3 per cent of the series

TREATMENT

At the Orthopaedic Hospital of the Invalid Foundation coxa plana has been conservatively treated The main principle of treatment has been the prevention of weight bearing on the affected hip In unilateral cases weight

relief has been accomplished with Thomas splint and elevation of the opposite shoe In bilateral cases where non weight bearing on both hips has been conditional this has been secured by bed rest One of the present patients was treated by bilateral Thomas splints Until 1957 patients were hospitalized only if the diagnosis was uncertain or if the joint exhibited marked contracture Since 1957 the pattern of treatment has been as follows Hospitalization for three to eight weeks during which the patient was kept in bed Traction was used if contracture of the hip was present A Thomas splint was manufactured fitted and adjusted Towards the end of the hospitalization period the patient practiced walking with the splint the fit of which was further adjusted When the patient had learned to walk with a *Thomas splint he was discharged and his parents* were informed as to the importance of strictly following the prescriptions regarding the use of the splint Subsequent follow up examinations were done at the Outpatient Department Exceptions from this routine were made in 1958 in particular when unfortunately for certain administrative reasons admission to the hospital was difficult in many cases

Table 11 shows the kind of treatment prescribed in the present cases The first group comprises the patients registered during the first few years covered by this study and some bilateral cases from more recent years At a later follow up examination of these cases it was found that the treatment prescribed had often been so inadequately carried out that no major influence on the course of the disease can be accorded to it These cases were classified as untreated (cf p 41)

T BLE 11 — *Treatment prescribed at the Orthopaedic Hospital of the Invalid Foundation*

	No of cases
Bed rest and/or crutch walking at home	29
Bed rest with traction at home	4
Thomas splint	190
Hospitalization + Thomas splint	27
Total	250

In a number of cases diagnosed elsewhere the patients had received some *kind of treatment as shown in Table 12 before being seen at the Orthopaedic* Hospital of the Invalid Foundation

It is seen in Table 12 that Thomas splint had been prescribed elsewhere in very few cases

TABLE 12 — *Treatment before the first examination at the Invalid Foundation*

	No of cases
Sparing use of limb crutches	22
Bed rest	44
Traction	17
Plaster cast	21
Thomas splint	8
Total	112

If the non weight bearing treatment indicated in Table 12 was regarded as adequately carried out it was included in the data regarding the duration of such treatment.

Non weight bearing treatment was continued until reconstruction had advanced so far that the radiological appearance of the epiphysis was almost uniform and a large proportion of the epiphysis showed a normalized structure on the radiographs

The duration of non weight bearing treatment is seen in Table 13

TABLE 13 — *Duration of non weight bearing in 194 cases*

Years	No of cases
1	32
1—2	85
2—3	62
3—4	14
over 4	1

Mean duration of non weight bearing 2 3 years

After the completion of non weight bearing treatment the patients were told not to strain their hips for a further two or three years or until primary healing had been achieved During this time school gymnastics and athletics were forbidden

As a rule Thomas splint was abandoned gradually being used during half the day for instance at school while the child was allowed to walk without it during the rest of the time

Not in a single case have we had to revoke the decision to let a patient abandon Thomas splint The radiological check ups invariably showed that the epiphysis had tolerated the strain Usually the very first follow up examination showed increased reconstruction

END-RESULTS

In the present study the time from the onset of the first symptoms until the last (or only) radiological examination is indicated in Table 14

TABLE 14 — *Time from onset to last or only examination in 76 cases of coxa plana.*

Years	No of cases	Years	No of cases
1	18	9	20
2	12	10	23
3	15	11	16
4	20	12	10
5	26	13	9
6	35	14	1
7	27	15	4
8	24	16 or more	16

The longest period between the onset of symptoms and the last radiological examination was 36 years

Primary healing is used in the present series to denominate the condition prevailing when the reparative process in the femoral epiphysis had advanced so far that the latter had attained its final shape and the bony structure of the epiphysis had been normalized In this stage the epiphysis was uniform provided that no loose bodies remained as in osteochondrosis dissecans

Ultimate healing is used to denominate the stage when growth was completed

Since the *shape of the epiphysis* does not change to any appreciable degree after primary healing has taken place that is during the remainder of the growing period (WALDENSTRÖM 1923) the cases showing primary and ultimate healing were united when the end results in the femoral head were assessed

Definition of the degree of healing The femoral head was regarded as spherical (*good result*) if its outline could be precisely fitted into one of the circles of the plastic protractor and if the radii of the circles formed by the outline on the frontal and lateral views did not differ from each other by more than 1 mm A difference of 1 mm between the radii on the frontal and lateral views was noted on the unaffected side in many cases

The femoral head was evaluated as elliptical (*fair result*) if its outline was regularly convex without fitting into any of the circles of the protractor and if the difference between the radii of the outlines on the frontal and lateral views exceeded 1 mm

The femoral head was evaluated as irregular (*poor result*) in those cases where it could not be regarded as spherical or elliptical

In the present series a total of 165 treated hips in 119 unilateral and in 23 bilateral cases showed either primary or ultimate healing

TABLE 15 — *Relationship between radiological end results and age at onset in 165 treated hips*

End results	Onset age in years											
	2—3		4—5		6—7		8—9		10—14		Total no of hips	%
	No	%	No	%	No	%	No	%	No	%		
Good	10	90 9	31	64 6	30	49 2	10	31 2	—		81	49 1
Fair	1	9 1	13	27 1	14	22 9	6	18 8	1	7 7	35	21 2
Poor	—		4	8 3	17	27 9	16	50 0	12	92 3	49	29 7
	11	100	48	100	61	100	32	100	13	100	165	100

TABLE 16 — *Relationship between radiological end results and duration of symptoms before treatment in 165 treated hips*

End results	Time in months												Total no of hips	%
	0—1		2—3		4—5		6—7		8—12		13—24			
	No	%	No	%	No	%	No	%	No	%	No	%		
Good	23	74	21	65 6	9	45	16	51 6	4	18 2	8	27 6	81	49 1
Fair	6	19 5	3	9 4	8	40	5	16 2	3	13 6	10	34 4	35	21 2
Poor	2	6 5	8	25	3	15	10	32 2	15	68 2	11	38	49	29 7
	31	100	32	100	20	100	31	100	22	100	29	100	165	100

TABLE 17 — *Relationship between radiological end results and stage of the process at the institution of treatment*

End results	Stage						No of hips
	Initial		Fragmentation		Reparative		
	No of hips	%	No of hips	%	No of hips	%	
Good	55	56 7	25	39 0	1	25 0	81
Fair	18	18 6	16	25 0	1	25 0	35
Poor	24	24 7	23	36 0	2	50 0	49
Total	97	100 0	64	100 0	4	100 0	165

In Tables 15 16 and 17 the radiological end results are correlated with onset age duration of symptoms and stage of the process at the institution of treatment

Enlargement of the femoral head In order to obtain an idea of the enlargement of the femoral head in those cases where it healed as spherical the radii of the outline circles of both heads were compared in unilateral cases To this end the cases were divided into primarily healed (42) and ultimately healed (21) In no case was the radius of the affected head smaller than that of the unaffected head In the group of primarily healed cases there were 7 with the same radius on both sides The difference between the two radii varied between 1 and 5 mm the mean being 2 6 mm In the group of ultimately healed cases one showed the same radius on both sides The difference varied between 1 and 10 mm the mean being 3 7 mm

In the primarily healed group the radii of the affected heads exhibited a mean enlargement of 11 9 per cent as compared with the unaffected heads The corresponding figure for the ultimately healed group was 13 6 per cent The corresponding mean increases in the volume of the head were 38 5 and 46 4 per cent respectively

Discussion This analysis demonstrates the well known fact that the head of the femur in a coxa plana hip as a rule is enlarged as compared with the unaffected side

In the present analysis the flattening of the epiphysis was disregarded while in the above mentioned calculations of index it has been taken into account It is very difficult however to estimate the degree of flattening of the epiphysis since the height of the latter shows a wide variation even in spherically healed cases owing to a cranially directed convexity in the metaphyseal plane In these cases the height of the epiphysis is hardly of any practical significance however It is the shape of the head that is decisive irrespective of whether it is a hemisphere consisting of the epiphysis alone or consists of a crescent shaped epiphysis the basal interior portion of which is filled out by the metaphysis

Untreated cases The present series includes both entirely untreated coxa plana hips and cases in which the treatment had been so recently instituted or so inadequately carried out that no therapeutic significance can be accorded to it The primary or ultimate healing could be evaluated in 78 such hips (67 cases) The end results are shown in Table 18

The surprisingly large number of good results in this group is accounted for by the fact that it includes 4 very slight abortive unilateral cases and 12 bilateral cases in which the better untreated hip exhibited slight abortive

TABLE 18 — *Relationship between radiological end results and age at onset in 78 untreated hips*

Onset age in years	Good	Fair	Poor	No of hips
2—3	1	—	1	2
4—5	7	1	4	12
6—7	5	5	15	25
8—9	1	2	12	15
10—11	3	—	6	9
12—14	1	1	2	4
unknown			11	11
Total	18	9	51	78
Per cent	23	11	66	100

changes Only two of the untreated cases which healed with spherical femoral heads showed fragmentation of the epiphysis

If these abortive cases are omitted the end results in the untreated group are as follows

Good 3 2 per cent Fair 14 5 per cent Poor 82 3 per cent

When these results are compared with the end results in the treated group (Table 15) the difference is striking

Cases under treatment The series includes 61 patients (83 hips) who are still under treatment or have failed to attend at follow up examinations In these cases it is not possible to say anything regarding the end result

Special factors affecting the end results

In the present series the following factors were found to affect the end-results

Osteochondrosis dissecans	in 16	cases	(3	untreated)
Subluxation	» 45	»	(30	»)
Secondary arthrosis	» 20	»	(17	»)

Comparison of the present observations with previous reports

Sex incidence The data of different authors agree in that coxa plana is commoner in boys than in girls In Table 19 the relevant figures from some of the more extensive series are indicated

TABLE 19 — *Sex incidence of coxa plana in other series*

Investigator	No of cases	Males %	Females %
Levy et al (1942)	102	91.0	9.0
Bernbeck (1951 a)	369	77.0	23.0
Sundt (1949)	153	78.0	22.0
Kite et al (1952)	165	86.0	14.0
Helbo (1953)	204	77.4	22.6
Goff (1954)	103	83.0	17.0
Ryder et al	104	82.2	17.8
Evans (1958)	52	75.0	25.0
Wansbrough et al (1959)	129	81.4	18.6
Carpenter (1960)	90	84.5	15.5
Peić (1962)	189	79.4	20.6
Mose (1964)	257	80.6	19.4

The sex incidence in the present series — 80.8 per cent males and 19.2 per cent females — is in good agreement with the figures in Table 19

TABLE 20 — *Distribution of coxa plana according to affected side in other series*

Investigator	No of cases	Right side	Left side	Both sides %
Sundt	153	40.5	47.0	12.5
Helbo survey of the literature	250	57.0	38.0	5.0
Helbo own series	204	48.0	44.6	7.4
Goff	103	42.5	40.0	17.5
Ryder et al	104	42.3	42.3	15.4
Evans	58	48.2	41.5	10.3
Wansbrough et al	129	?	?	17.8
Peić male patients	150	56.0	38.7	15.3
Peić female	39	33.4	56.4	10.2
Mose	257	?	?	10.9

Affected side The observations regarding the affected side in certain earlier series are compiled in Table 20 Most reports show a slight preponderance for the right side SUNDT had slightly more left sided than right sided cases while the two sides were equally represented in RYDER s series PEIC observed a preponderance of right-sided lesions in the male patients while the female group showed a left sided preponderance

In the present series a slight preponderance was noted for the left side i e 44 per cent against 38 per cent right sided while the proportion of bilateral cases was 18 per cent (Table 6) Contrary to PEIC s finding there was no difference between males and females in regard to the frequency of right-sided and left sided lesions

The frequency figures for bilateral cases indicated in the literature show a wide variation (Table 20) This may perhaps be accounted for by the fact that in bilateral cases the lesion in one hip is often very slight and may escape recognition for instance if satisfactory lateral views are not available

Age at onset In the present series (Table 8) there was an obvious accumulation of cases in the age group 6—7 years which was represented by 39 3 per cent

STAHL (1948) calculated the onset age by reducing the age at the first radiological examination by an average of three nine or eighteen months depending on whether the process was in the initial fragmentation or early reparative stage at the time of the first examination According to these calculations the mean age at onset was 6 6 years in STAHL s series comprising 103 hips In other series published the maximum frequency varies to some extent The following authors for instance have observed a peak for the age groups as listed here BERNBECK (1951 a) 8 years WANSBROUGH *et al* (1959) 7 years GOFF (1954) 6 years HELBO (1953) and PONSETI & COTTON (1961) 5—6 years O GARRA (1959) HERZOG (1961) and MOSE (1964) 5 years PEIC (1962) 4—6 years

Duration of symptoms from onset to diagnosis It is seen in Table 9 that the duration of symptoms from onset to diagnosis was an average of 9 6 months in the present series

HELBO (1953) described a group of 66 patients with coxa plana in which the duration of symptoms was an average of 3 9 months in 39 cases an average of 6 months in 6 and 10 1 months in 21 In EVANS (1958) series the duration was one to 36 months the mean being 6 months CARPENTER & POWELL (1960) indicated a mean duration of symptoms of 7 months and 24 days In a series of 107 patients with coxa plana described by RALSTON (1961) treatment could be instituted 3 months after onset in 49 cases (46 per cent) In the series described by WANSBROUGH *et al* (1959) comprising 106 cases fifty per cent were diagnosed within 3 months and in two thirds the diagnosis was made within 6 months after onset

Stage of the process at diagnosis As is seen in Table 10 slightly less than half the present cases of active coxa plana were in the initial stage at the time when the diagnosis was made 33 7 per cent were in the fragmenta-

tion stage and 15 8 per cent exhibited more or less advanced reconstruction

In HELBO s (1953) series of 66 patients treated by protracted bed rest 68 per cent were initial cases and 32 per cent showed fragmentation on admission to hospital WANSBROUGH *et al* (1959) described 55 5 per cent of their cases as very early or early and 44 5 per cent as advanced or very advanced Among 90 patients examined CARPENTER & POWELL (1960) found that 73 3 per cent had minimal or moderate and 26 7 per cent advanced destructive changes

End results In Table 21 the end results in a number of previous studies are compiled There are wide variations in the selection of cases the treatment employed and the methods of evaluation of the end results in both the series treated by bed rest and in those treated by various non weight

TABLE 21 — *Relationship between end results and treatment in different series reported in the literature*

Investigator	No of cases	Treatment	Results in		
			Excellent and good	Fair	Poor
Fike 1950	11	Bed rest without splints	36	28	36
Fike	23	Bed rest with splints	83	10	7
Mindell et al 1951	28	Bed rest	53 5	17 7	28 8
Herndon et al 1952	33		61 0	39 0	0
Helbo 1953	61		82 0	16 4	1 6
Goff 1954	65		57 0	29 2	13 8
Hauge 1956	132		32 6	40 0	27 4
Ratliff 1956	41		43 7	36 8	19 5
Evans 1958	52		29 0	40 0	31 0
Evans et al 1958	24		62 5	20 8	16 7
Wansbrough et al 1959	14		50 0	36 0	14 0
Herzog 1961	73		77 5	14 0	8 5
Mose 1964	78	Strict bed rest	58 0	17 0	25 0
Mose	70	Mobile bed rest	61 0	20 0	19 0
Mindell et al 1951	32	Crutches or walking caliper	72 0	15 5	12 5
Evans et al 1958	24	Crutches and Snyder s sling	58 3	16 7	25 0
Herzog 1961	34	Walking caliper	44 0	24 0	32 0
Wansbrough et al 1959	76	Taylor caliper	75 0	11 8	13 2
Wansbrough et al	16	Thomas splint	25 0	75 0	25 0
Mose 1964	71	Walking caliper	45 0	17 0	38 0

In the present series a slight preponderance was noted for the left side, i.e. 44 per cent against 38 per cent right sided, while the proportion of bilateral cases was 18 per cent (Table 6). Contrary to PEIC's finding, there was no difference between males and females in regard to the frequency of right sided and left sided lesions.

The frequency figures for bilateral cases indicated in the literature show a wide variation (Table 20). This may perhaps be accounted for by the fact that in bilateral cases the lesion in one hip is often very slight and may escape recognition, for instance if satisfactory lateral views are not available.

Age at onset. In the present series (Table 8) there was an obvious accumulation of cases in the age group 6—7 years which was represented by 39.3 per cent.

STAHL (1948) calculated the onset age by reducing the age at the first radiological examination by an average of three, nine or eighteen months, depending on whether the process was in the initial fragmentation or early reparative stage at the time of the first examination. According to these calculations the mean age at onset was 6.6 years in STAHL's series comprising 103 hips. In other series published, the maximum frequency varies to some extent. The following authors, for instance, have observed a peak for the age groups as listed here: BERNBECK (1951 a) 8 years, WANSBROUGH *et al.* (1959) 7 years, GOFF (1954) 6 years, HELBO (1953) and PONSETI & COTTON (1961) 5—6 years, O GARRA (1959), HERZOG (1961) and MOSL (1964) 5 years, PEIC (1962) 4—6 years.

Duration of symptoms from onset to diagnosis. It is seen in Table 9 that the duration of symptoms from onset to diagnosis was an average of 9.6 months in the present series.

HELBO (1953) described a group of 66 patients with coxa plana in which the duration of symptoms was an average of 3.9 months in 39 cases, an average of 6 months in 6 and 10.1 months in 21. In EVANS (1958) series the duration was one to 36 months, the mean being 6 months. CARPENTER & POWELL (1960) indicated a mean duration of symptoms of 7 months and 24 days. In a series of 107 patients with coxa plana described by RALSTON (1961) treatment could be instituted 3 months after onset in 49 cases (46 per cent). In the series described by WANSBROUGH *et al.* (1959) comprising 106 cases, fifty per cent were diagnosed within 3 months, and in two thirds the diagnosis was made within 6 months after onset.

Stage of the process at diagnosis. As is seen in Table 10, slightly less than half the present cases of active coxa plana were in the initial stage at the time when the diagnosis was made, 33.7 per cent were in the fragmenta-

a large number of authors emphasize that the earlier treatment is instituted the better are the results (Brandes 1920 Severin 1942 Sjovall 1943 Mindell & Sherman Helbo Goff Wansbrough *et al* Carpenter & Powell and others)

The present observations confirm the above mentioned observation It is seen in Table 16 that in over half of the cases which healed with a spherical femoral head treatment had been instituted within three months after the onset of symptoms while only about 15 per cent of the patients with good results had been ill for over seven months when the diagnosis was made

In the present series the mean duration of symptoms before the institution of treatment was 9 6 months (Table 9) This seems to some extent at least to account for the poorer end results in this series as compared with some of those presented in Table 21 In the majority of the earlier series a shorter mean duration of symptoms has been indicated

Ralston (1961) arrived at deviating results in regard to the relationship between onset age and end results His series consisted of 43 cases of unilateral coxa plana Treatment (recumbency with Buck s extension and daily progressive resistance exercise) was in all cases instituted within three months after the onset of symptoms Statistical analysis of the comprehensive *quotient after healing had begun showed no correlation between onset* age and degree of healing The age at onset as compared with the duration of the period of recovery gave a poor correlation and the correlation between onset age and the maximal percentage of epiphyseal involvement was also poor

Stage of the process at institution of treatment and end results This point was discussed by Helbo Hauge, Wansbrough *et al* and Carpenter & Powell among others who found that the end results were better if the treatment had been instituted before the process had advanced to the stage of fragmentation

The present series (Table 17) shows a clear tendency towards better radiological end results when treatment was instituted at an early stage of the disease

Factors affecting the end results Haas (1937) Freund (1939) Brailsford (1943) Hermodsson (1944) Sundt (1949) Goff (1954) Perttila (1954) Ratliff (1956) Evans (1958) Jenkins (1958) Freehafer (1960) and Morris & McGibbon (1962) have described occasional cases in which a condition resembling osteochondrosis dissecans was associated with coxa plana Mose (1964) detected 8 cases of osteochondrosis dissecans in his

series All these patients belonged to the higher age groups and in none of these cases were there any radiological changes discernible in the epiphyseal line or the metaphysis

In the present series osteochondrosis dissecans was detected in 17 hips *i e* in 5 2 per cent of the 326 hips with coxa plana examined In one bilateral case osteochondrosis dissecans was also bilateral Four of these patients belonged to the age group 5—7 years at the onset of the disease and 12 patients were 8—11 years at onset In 13 cases growth was completed In 8 there were no or minimal metaphyseal changes In 9 hips osteochondrosis dissecans developed in connexion with severe metaphyseal disturbances In this respect the observations in the present series differ from those of MOSE

In 7 of the cases under discussion there was a history of trauma The experimental investigations of A LANGENSKIOLD (1955) and TALLQVIST (1962) regarding the development of osteochondrosis dissecans lend strong support to the view that the cause of this lesion is a *cartilage fracture* during the growing period In the present series of 276 cases there were 48 (17 3 per cent) in which trauma was mentioned in the history Among those showing osteochondrosis dissecans 43 7 per cent had a history of trauma This is strongly suggestive of a causal relationship between trauma and osteochondrosis dissecans in coxa plana

To a certain extent this observation also lends support to NAGURA s (1937) theory that the cause of coxa plana is a compression fracture in the chondroepiphysis

In this connexion it may also be mentioned that KIRSCH (1961) described a case of coxa plana which initially exhibited the kind of picture typical of osteochondrosis dissecans

Regarding the frequency of subluxation in association with coxa plana there are few data in the literature SUNDT (1949) observed subluxation in 104 out of 153 and PERTTILA (1954) in 17 out of 33 finally healed cases EVANS (1958) detected subluxation in 42 out of 58 coxa plana hips He pointed out that the subluxation was very slight in the patients with good and fair end results

In the present series subluxation was noted in 45 hips out of 326 (13 8 per cent) Thirty of these were untreated and poorly healed while in 15 hips the result of treatment was poor

That coxa plana predisposes to secondary arthrosis has been emphasized by several authors *e g* MOLLER (1926) EYRE BROOK (1936) and SUNDT (1949)

In the present series secondary arthrosis was observed in 20 cases 17 of which were neglected These patients sought medical aid on account of symptoms in the hip due to the complicating arthrosis In 3 instances arthrosis developed in poorly healed cases during the time of observa tion

OBSERVATIONS WITH A BEARING ON AETIOLOGICAL FACTORS

Trauma

In 10 cases (3 6 per cent) of the present series the disease was preceded by a single trauma which may be considered directly related to the develop ment of coxa plana

Case 22 A girl aged 3 had fallen from the second floor and injured the hip region

Case 24 A girl aged 6 had had a traumatic luxation of the hip

Case 43 A boy aged 11 had been run over by a sledge resulting in con tusion and immediate pain in his hip

Case 74 A boy aged 7 had fallen from a tree and bruised the hip region

Case 141 A boy aged 6 had fallen from a pile of wood resulting in con tusion and immediate pain in his hip

Case 148 A boy aged 6 had bruised the hip Ecchymoses of the hip region resulted

Case 176 A boy aged 8 had fallen from a bar during gymnastics resulting in immediate severe pain in his hip

Case 191 A girl aged 9 had bruised her hip and been hospitalized on this account

Case 196 A boy aged 8 had fallen from a rafter in a barn and experienced immediate pain in his hip

Case 216 A boy aged 8 had fallen from a moving merry go-round and bruised his hip There was immediate pain

Furthermore in 31 cases (11 2 per cent) a single trauma was mentioned *e g* a fall during play or when riding a bicycle or skiing jumping from a rail or a stair a kick by a playmate but these everyday incidents had often occurred long before any hip symptoms were noted and must be regarded with great reserve as possible aetiological factors

In addition the series contains 7 cases (2 5 per cent) in which repeated trauma or excessive straining of the hip at the time of onset of symptoms can be taken into consideration In 3 cases the child had jumped innumerable

times from a roof or a tree In 1 case the symptoms had been preceded by intensive training in ski jumping in 3 cases by energetic training in bicycle riding

Infection

An infectious aetiology seems tenable in the following of the present cases

Case 102 A boy aged 5 started limping and complained of pain in the left knee in association with acute tonsillitis On radiological examination nothing noteworthy was observed in the knee About four months later coxa plana in an early stage of fragmentation was observed in the left hip

Case 54 A boy aged 11 fell ill with fever and hip pain Three months later contracture and limitation of movement in the right hip was observed at our Hospital A radiograph revealed marked condensation and moderate flattening of the right femoral epiphysis and a large step shaped defect in the ventral margin of the metaphysis Coxa plana in a late initial stage was diagnosed (Fig 4) The head socket distance was increased medially and slightly narrower than normal cranially The outline of the acetabulum was blurred The patient was fitted with Thomas splint At a follow up examination one year later the femoral epiphysis was in a stage of reconstruction The metaphyseal defect had been filled up to some extent but the head socket distance was still larger than normal medially The mobility of the hip



Fig 4 Case 54 boy aged 11 fell ill with fever and hip pain Three months later contracture and limitation of movement in the right hip Radiographs at this time *a* frontal — and *b* lateral view Marked condensation and moderate flattening of the femoral epiphysis and a large step shaped defect in the ventral margin of the metaphysis

showed some improvement The patient has failed to attend at suggested later follow up examinations

Case 149 A boy aged 3 years and 2 months developed symptoms in the left hip in connexion with acute appendicitis Appendicectomy was performed Three months later radiological examination revealed signs of epiphysiolysis of the proximal femoral epiphysis Typical coxa plana developed (Fig 5)

Case 161 A girl aged 7 was hospitalized for one month on account of burns Subsequently she showed a limp Three to four months later coxa plana on the left side was observed

Case 78 A boy aged 6 fell against a stump and sustained a wound in the right inguinal fold Wound infection developed and he was treated in bed for a month Subsequently he showed a persistent limp A radiological examination performed eight years later in our Hospital showed coxa plana on the right side in a late reparative stage

Hereditary and constitutional factors

Data regarding the possible occurrence of coxa plana in the patient s family was elicited in 172 of the present cases In 11 cases (6 4 per cent) radiologically verified coxa plana was recorded in members of the family

TABLE 22 — *Birth order in 153 cases of coxa plana and of all 585 children in the coxa plana families concerned*

Birth order	No of cases of coxa plana	No of children	Ratio
I	51	153	1 3 0
II	50	141	1 2 8
III	24	105	1 4 3
IV	5	62	1 12 4
V	8	42	1 5 3
VI	1	29	1 29 0
VII	9	23	1 2 6
VIII	3	15	1 5 0
IX	1	9	1 9 0
X	1	4	1 4 0
XI	—	1	—
XII	—	1	—
Total	153	585	

times from a roof or a tree In 1 case the symptoms had been preceded by intensive training in ski jumping in 3 cases by energetic training in bicycle riding

Infection

An infectious aetiology seems tenable in the following of the present cases

Case 102 A boy aged 5 started limping and complained of pain in the left knee in association with acute tonsillitis On radiological examination nothing noteworthy was observed in the knee About four months later coxa plana in an early stage of fragmentation was observed in the left hip

Case 54 A boy aged 11 fell ill with fever and hip pain Three months later contracture and limitation of movement in the right hip was observed at our Hospital A radiograph revealed marked condensation and moderate flattening of the right femoral epiphysis and a large step-shaped defect in the ventral margin of the metaphysis Coxa plana in a late initial stage was diagnosed (Fig 4) The head socket distance was increased medially and slightly narrower than normal cranially The outline of the acetabulum was blurred The patient was fitted with Thomas splint At a follow up examination one year later the femoral epiphysis was in a stage of reconstruction The metaphyseal defect had been filled up to some extent but the head socket distance was still larger than normal medially The mobility of the hip

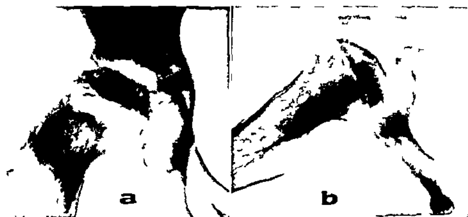


Fig 4 Case 54 boy aged 11 fell ill with fever and hip pain Three months later contracture and limitation of movement in the right hip Radiographs at this time *a* frontal — and *b* lateral view Marked condensation and moderate flattening of the femoral epiphysis and a large step shaped defect in the ventral margin of the metaphysis



Fig 5 Case 149 boy aged 3 years and 2 months developed symptoms in the left hip in connexion with acute appendicitis Appendicectomy was performed Three months later radiological examination revealed signs of epiphysiolysis of the proximal femoral epiphysis *a* frontal and *b* lateral view Later typical coxa plana with slight fragmentation of the epiphysis but without metaphyseal changes developed *c—d* Treated with Thomas splint End result good *e—f*

Birth order In 153 cases the birth order of the patient was recorded Table 22 shows the distribution of the cases by birth order groups and the relationship between these and the total number of children in the respective groups in the families concerned

Bone age Bone age was determined by GREULICH & PYLE s (1959) method on radiographs of the bones of the hand in 61 cases of coxa plana Some of these patients did not belong to the present series The cases were taken at

random and represented different stages of the disease Table 23 shows the differences between bone age and chronological age in the cases concerned

TABLE 23 — *Skeletal age in 64 cases of coxa plana in different stages of the disease*

Stage	Delayed		Normal	Accelerated		Total no of cases
	No of cases	Months (range)	No of cases	No of cases	Months (range)	
Initial	6	19 (9—31)	—	—		6
Fragmentation	11	21 (12—43)	4	1	7	16
Reparative	11	19 (10—32)	12	1	13	24
Definitive (Growing period)	9	18 (6—30)	6	3	12 (9—13)	18
Total	37	19	22	5	11	64

Discussion

Trauma From the survey of the literature it appeared that many authors regard trauma as a possible cause of coxa plana

In the present series trauma was mentioned in 18 cases (17 3 per cent) but in the majority of these the statement has to be viewed with great reserve Parents usually look for a cause when their child starts limping or complains of pain in the hip Then the child itself or somebody in the family or its environment recalls a previous accident which is considered responsible for the disease although it may be entirely insignificant

In regard to repeated minor traumata it is difficult to decide whether they are of aetiological significance in coxa plana It seems possible that they play a part as a contributory or precipitating cause

In 3 6 per cent of the present cases, however trauma appears to be a factor that significantly influenced the development of the disease

Infection As was already mentioned in the survey of the literature a number of authors have suggested that inflammatory processes may lead to coxa plana

The present series contains only a few cases in which an inflammatory aetiology can be suspected In case 51 it seems probable that coxa plana developed in connexion with acute synovitis of the hip joint

Case 149 (Fig 5) exhibited an obvious wedge shaped gap in the epiphyseal line ventrally This observation corroborates the view chiefly advanced by PONSETI & MCCLINTOCK (1956) that loss of cohesion of the cartilage matrix is the cause of the circulatory disturbance leading to necrosis of the epiphysis This loss of cohesion may be due to inflammation

Hereditary and constitutional factors Of the present patients 6 4 per cent had close relatives with radiologically verified coxa plana

HELBO calculated the incidence of coxa plana among the school children in Copenhagen as 0 44 pro mille MOSE (1964) reported frequencies of 0 08 pro mille among the population on Zealand and 0 09 pro mille in South Jutland If these figures are compared with the frequency of familial coxa plana observed in the present study *i e* 6 4 per cent it seems obvious that hereditary factors play a part in the development of the disease

One of the present patients who came from a family with 7 children had 3 siblings with coxa plana The lesion was unilateral in all four cases with typical radiological changes of the same type One of the four was a heterozygous twin whose twin sister was unaffected All the children were otherwise in good health and well developed The parents were healthy but 2 cousins (not brothers) of the father s have a limp due to shortening of one extremity

Birth order GOFF (1954) found that the first child most frequently develops coxa plana This observation was corroborated by PRIC (1962) Table 22 shows that in the present series too first and second children were most numerous among the patients with coxa plana But this is due to the fact that the absolute number of first and second children was largest in the families concerned These constituted about fifty per cent The ratios between the number of coxa plana children in the different birth order groups and the total number of children in these groups show that the morbidity was not higher among first and second children than among those born later The table shows the highest incidence in the group of seventh children *i e* 1 2 6 and the lowest — 1 29 — in the group of sixth children The wide variation is obviously due to the fact that the series analysed is too small The study seems however to indicate that the birth order is insignificant

Bone age In Table 23 it is seen that in the cases examined bone age and chronological age coincided in 22 In 37 cases the bone age was delayed by

random and represented different stages of the disease Table 23 shows the differences between bone age and chronological age in the cases concerned

TABLE 23 — *Skeletal age in 64 cases of coxa plana in different stages of the disease*

Stage	Delayed		Normal	Accelerated		Total no of cases
	No of cases	Months (range)	No of cases	No of cases	Months (range)	
Initial	6	19 (9—31)	—	—		6
Fragmentation	11	24 (12—48)	4	1	7	16
Reparative	11	19 (10—32)	12	1	13	24
Definitive (Growing period)	9	18 (6—30)	6	3	12 (9—13)	18
Total	37	19	22	5	11	64

Discussion

Trauma From the survey of the literature it appeared that many authors regard trauma as a possible cause of coxa plana

In the present series trauma was mentioned in 48 cases (17 3 per cent) but in the majority of these the statement has to be viewed with great reserve Parents usually look for a cause when their child starts limping or complains of pain in the hip Then the child itself or somebody in the family or its environment recalls a previous accident which is considered responsible for the disease although it may be entirely insignificant

In regard to repeated minor traumata it is difficult to decide whether they are of aetiological significance in coxa plana It seems possible that they play a part as a contributory or precipitating cause

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VI. THE COURSE OF THE RADIOLOGICAL CHANGES IN COXA PLANA

JONSÄTER modified WALDENSTRÖM's (1923) classification of stages by uniting his last two groups (the growing period and the definitive stage) for the reason that the femoral head attains its final shape during the growing period. In this paper JONSÄTER's classification into initial stage, fragmentation stage, reparative stage and definitive stage is used.

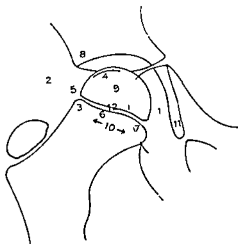


Fig. 6. Early radiological signs in coxa plana. 1. Increased head socket distance. WALDENSTRÖM's sign (1934). 2. Bulging of the joint capsule. FERGUSON & HOWORTH (1934). 3. Rarefaction DREHMANN (1914) or rounding GAGE (1933) of the lateral margin of the metaphysis. 4. A strip shaped subcortical translucent area ventro-laterally in the epiphysis. FREUND (1930). 5. Rarefactions in the lateral outline of the epiphysis close to the epiphyseal plate. FREUND (1930). 6. Band shaped osteoporosis in the metaphysis close to the epiphyseal plate. WALDENSTRÖM (1923). 7. Translucent area in the medial metaphyseal zone. GILL (1940). 8. Changes in the roof of the acetabulum. FROMME (1921). 9. The bony epiphysis smaller than in the unaffected hip, shape and structure of the epiphysis normal. BERGMANN (1927). 10. Enlargement of the neck of the femur close to the epiphyseal plate. FÈVRE & LAGRANGE (1936). 11. The tear shaped phenomenon, widening of Köhler's tear shaped figure. HALKIER (1936). 12. Thickening of the epiphyseal plate. HOWORTH (1939).



Fig 7 a—c

EARLY RADIOLOGICAL SIGNS

The importance of early diagnosis and early institution of treatment in coxa plana has been emphasized by the majority of authors The recognition of early radiological signs is therefore a point of major interest

Earlier observations

WALDENSTROM (1923) began his definition of the initial stage as follows »To begin with only limping without any change in the X ray picture»



Fig 7 Case 141 boy aged 5 years and 10 months at onset Limping after fall from a pile of wood *a* and *b* 3 weeks after onset increased head socket distance slight swelling of the soft parts lateral to the left hip joint slight general osteoporosis of the hip region and thickening of the epiphyseal plate No structural changes of the epiphysis or changes of its outline Bed rest with extension for six weeks *c* and *d* 9 weeks after onset the radiological state was the same as before No clinical symptoms Weight bearing was allowed and *f* 22 weeks after onset a large translucent area in the ventral part of the epiphysis which was slightly flattened Treated with Thomas splint for 3 years After slight fragmentation and slight metaphyseal changes healing with spherical head

Many other authors have come to the conclusion that coxa plana begins with a prodromal stage during which no radiological changes or only changes of the soft parts are observable (FREUND 1930 FERGUSON &



Fig 7 a—c

EARLY RADIOLOGICAL SIGNS

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Case 141 (Fig 7) exhibited Waldenstrom s sign i e increased head socket distance slight swelling of the soft parts lateral to the left hip joint slight general osteoporosis of the hip region and thickening of the epiphyseal plate two months after onset No structural changes of the epiphysis or changes of its outline were discernible Later typical changes developed

Case 65 (Fig 8) Three months after onset the radiographs showed reduced height and breadth of the right bony epiphysis The calcium concentration outline and structure of the latter were completely normal The head-socket distance was the same as on the unaffected side Later this case showed moderate fragmentation and a good end result

Case 123 (Fig 9) A bilateral case At the first examination the left hip was evaluated as radiologically normal At a check up three months later the outline of the lateral pole of the epiphysis was irregular and exhibited a small defect This finding corresponds to the early sign described by FREUND (1930) Later typical changes developed

Case 124 (Fig 10) The only radiological sign was a small subcortical strip shaped translucent area proximally in the epiphysis Complete healing occurred without any other treatment than refraining from athletics and gymnastics for some weeks This case must be regarded as uncertain

The tear shaped phenomenon was observed in 25 cases of incipient coxa plana In 20 of these the phenomenon was obviously due to oblique projection caused by atrophy of the gluteal muscles on the affected side In 5 cases it could not be established whether the projection was oblique In a further 3 cases the tear shaped figure was narrower on the affected side than on the unaffected side

Discussion

Both previous reports and the present observations indicate that the early signs in coxa plana vary from case to case The radiological picture shown by case 141 (Fig 7 a) for instance is not pathognomonic of coxa plana it could just as well support a diagnosis of any kind of synovitis In uncertain cases it is of paramount importance to institute weight relief and keep the patient under observation for a sufficiently long time This has previously been emphasized by HOWORTH (1959) in particular

Most often the tear shaped phenomenon is probably due to oblique projection of the pelvis and this sign cannot be regarded as pathognomonic of coxa plana



Fig 8 Case 65 boy aged 7 at onset *a* and *b* 3 months after onset reduced height and breadth of the right epiphysis The calcium concentration outline and structure of the latter are completely normal The head socket distance is the same as on the unaffected left side Later this case showed moderate fragmentation and a good end result

Howorth 1931 Helbo 1953 Nova Monteiro 1951 Howorth 1959 Jacobs 1960 Ralston 1961)

Fig 6 demonstrates early radiological signs in coxa plana of the kind previously described in the literature

Observations on the present material

In the present series the radiological findings at the first examination were mostly *typical and indisputable owing to the fact that the disease* process was already advanced But in certain cases the first diagnosis was tentative Some of these may be described as examples of early signs

Case 141 (Fig 7) exhibited Waldenstrom s sign i e increased head socket distance slight swelling of the soft parts lateral to the left hip joint slight general osteoporosis of the hip region and thickening of the epiphyseal plate two months after onset No structural changes of the epiphysis or changes of its outline were discernible Later typical changes developed

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Discussion

Both previous reports and the present observations indicate that the early signs in coxa plana vary from case to case The radiological picture shown by case 141 (Fig 7 a) for instance is not pathognomonic of coxa plana it could just as well support a diagnosis of any kind of synovitis In uncertain cases it is of paramount importance to institute weight relief and keep the patient under observation for a sufficiently long time The has previously been emphasized by Howorth (19[illegible]) in particular

Most often the tear shaped phenomenon is probably due to oblique projection of the pelvis and this sign cannot be regarded as pathognomonic of coxa plana



Fig 9 a—c

CHANGES IN THE CAPITAL EPIPHYSIS

Initial stage

Observations on the present material This stage was counted from the onset of symptoms to the time when the bony epiphysis exhibited the first signs of fragmentation

Duration of the initial stage In the present series 117 hips were studied in the initial stage *i e* 101 in unilateral and 16 in bilateral cases The dura

d

e

Fig 9 Case 123 boy aged 7 years and 5 months ...
for five months before the first visit At th ...
shows fragmentation In the lateral outline of ...
tion which was overlooked Thomas splint on th ...
later *c* and *d* the rarefaction in the lateral ...
metaphyseal changes on the right side After a ...
of coxa plana on the left side with flattenin ...
6 months in bed Thomas splint on the left ...
sides Osteochondrosis d ...

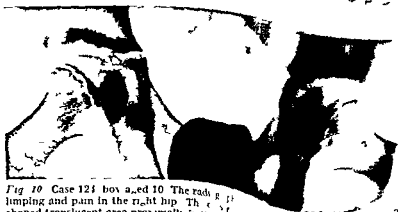


Fig 10 Case 124 boy aged 10 The radi ...
limping and pain in the right hip Th ...
shaped translucent area proximally in the ...
occurr d without any other treatment than ...
some ...

ay
osis
and
mani-

ation was

ated that a
not think

tion of the initial stage could be evaluated in 116 cases as shown in Table 24

Table 25 shows the relationship between the duration of the initial stage and the age at onset of the disease It is seen that *the duration of the initial stage was independent of the onset age*

TABLE 24 — *Duration of the initial stage in 116 cases*

Time in months	No of cases
under 6	57
6—12	59

Mean duration 5 6 months

TABLE 25 — *Relationship between duration of the initial stage and onset age in 116 cases*

Duration of initial stage in months	Onset age in years						
	2—3	4—5	6—7	8—9	10—11	12—14	No of cases
Under 6	4	17	26	7	2	1	57
6—12	5	19	22	7	6	—	59

The radiological changes occurring during this stage in the epiphysis consisted of depressions and breaks in the outline as a rule in its proximo-ventral portion translucent areas often subcortical and flattening and condensation These changes occurred almost invariably except in mild abortive cases in which condensation was mostly absent

The changes varied in degree from case to case and it goes without saying that variations were seen in one and the same case depending on how far the process had advanced

The strip shaped subcortical translucent area mentioned in connexion with early signs (p 57) was a relatively frequent sign in the initial stage It was transitory owing to the fact that the cortical lamella was resorbed in more advanced cases or pressed against the spongy bone A subcortical strip of this kind shown in Fig 11 (case 32) was observed in 43 cases This radiograph was taken five weeks after the onset of symptoms



Fig 11 Case 32 boy aged 9 Five weeks after onset Marked subcortical strip shaped translucent area in the lateral view *b*

Condensation of the epiphysis often occurred early in the initial stage In exceptional cases it was observable immediately before or in connexion with fragmentation Case 141 Fig 7 is an example of absent condensation

The height of the chondroepiphysis remained unaltered during the initial stage This was shown by the fact that the distance from the epiphyseal cartilage to the socket of the acetabulum on the lateral view was the same as on the unaffected side In some cases with a »vacuum phenomenon« on the radiographs the height of the chondroepiphysis could be measured directly on the pictures

Discussion of the initial stage The duration of the initial stage was indicated by WALDENSTRÖM as a half to one year HELBO reported a mean duration of 12 months in his series the variation being 5 to 18 months

BERGSTRAND (1961) observed subcortical fissures or changes of the outline in the proximal portion of the femoral epiphysis in all cases of his series These changes were demonstrable until eight months after the onset of symptoms

The condensation observable in the epiphysis has been discussed by many authors AMSTAD (1916) CAAN (1924) and others ascribed it to sclerosis associated with increased deposition of calcium WIDERØE (1921) and LEHMANN (1940) regarded the condensation as a direct necrotic manifestation analogous to the sequestrum in osteomyelitis

AXHAUSEN & BERGMANN (1937) concluded that the condensation was due to compression of necrotic spongy bone

JONSÄTER (1953) who investigated this point histologically stated that a compression of the trabeculae obviously takes place but he did not think

that this phenomenon accounts for the marked condensation seen in early cases in which the epiphysis has still maintained its original shape

BERNBECK (1954) attributed the early condensation to an increase in inorganic substance due to penetration of chondroitinsulphuric acid from the surrounding cartilaginous tissue (»Kalk Phanerose«) The condensation seen in later stages he ascribed to compression of necrotic spongy bone

Case 43 Fig 12 in the present series is an example of intensive homogeneous condensation involving the whole of the epiphysis which showed very slight flattening In this case it is difficult to explain the condensation as due entirely to compression It seems more probable that it was a result of total necrosis with markedly increased calcium concentration (ivory epiphysis) A LANGENSKIOLD (1952) described a case of tuberculous spondylitis in which the first radiological examination showed an ivory vertebra *without any loss of substance or signs of compression*

BERGSTRAND (1961) found that the breadth of the bony epiphysis in the initial stage was smaller on the affected side and that the epiphyseal breadth

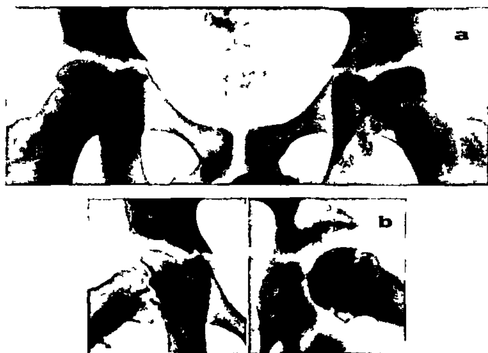


Fig 1 Case 43 boy aged 11 years and 3 months at onset *a* and *b* 5 months after an obvious single trauma Pronounced condensation without any appreciable flattening of the epiphysis Widening of the head socket distance

of the unaffected hip was fairly constantly attained and exceeded six to nine months after onset In the present study this point was not checked by systematic measurements but in many cases BERGSTRAND s finding could be confirmed as is shown in Fig 8 The phenomenon is attributable to inhibited growth of the necrotic ossific centre (PONSETI & COTTON 1961)

The shape and size of the chondroepiphysis was studied arthrographically by JONSATER (1953) and GOFF (1954) by measurement of the epiphyseal plate socket distance on radiographs by BERGSTRAND (1961) and in connexion with arthrotomy by HERZOG (1961) These investigations showed that the chondroepiphysis maintained its normal height throughout the initial stage and for part of the fragmentation stage

Fragmentation stage

In this study the fragmentation stage was counted from the time when the first radiological signs of fragmentation of the epiphysis were discernible until the time when the first signs of reconstruction could be seen on the radiographs

Observations on the present material On the basis of serial radiographs the *duration of the fragmentation stage* could be evaluated in 113 of the present cases as is seen in Table 26 The mean duration was 10 8 months

TABLE 26 — *Duration of the fragmentation stage in 113 cases*

Time in months	No of cases
Under 6	27
6—12	52
12—24	34

Mean duration 10 8 months

TABLE 27 — *Relationship between duration of the fragmentation stage and onset age in 113 cases*

Duration of fragmentation stage in months	Onset age in years												Total no of cases
	2—3		4—5		6—7		8—9		10—11		12—14		
	No of cases	%	No of cases	%	No of cases	%	No of cases	%	No of cases	%	No of cases	%	
Under 6	2	20	7	19	8	19	7	50	3	37 5	—		27
6—12	6	60	16	43	23	53	3	21	3	37 5	1	100	52
12—24	2	20	14	38	12	28	4	29	2	25	—		34

The relationship between the duration of the fragmentation stage and the age at onset of the disease appears in Table 27 A lower onset age does not seem to shorten the duration of the fragmentation stage which was 6 to 12 months in the majority of the cases with an onset age of 2 to 7 years Among those who were 8 to 11 years old at the time of onset of the disease the majority had a fragmentation stage of under 6 months but the number of cases is too small to allow of any definite conclusions Fragmentation was found to begin in the ventrolateral portion of the epiphysis and is best seen on the lateral view The structure of the epiphysis which usually showed condensation became irregular less dense areas occurred and the epiphysis became fragmented Fragmentation was often preceded by flattening of the bony nucleus and as fragmentation progressed the flattening was further increased

The degrees of fragmentation showed wide variations In some cases the epiphysis was divided into only two or three pieces while in others the osseous centre seemed to be completely fragmented In extreme cases only a few dense fragments were seen or a thin condensed lamella proximal to the metaphyseal surface

Discussion of the fragmentation stage Waldenström indicated the duration of the fragmentation stage as two to three years In Stahl s series the duration from onset of the disease to the beginning of the reparative stage was an average of 16 months with a variation of 7 to 31 months Helbo noted a mean duration of 26 months from the onset to the beginning of reconstruction in untreated and »symptomatically» treated patients and 16 months in those treated by protracted bed rest Bergstrand observed maximal fragmentation from 9 to 23 months after onset

Even in the first reports on coxa plana fragmentation of the femoral epiphysis was described Waldenström (1909) Perthes (1910) Schwarz (1914) and others regarded the fragmentation as a sign of a destructive process By contrast Calvé (1910) believed that the epiphysis had not been uniform but primarily separated into two or more small bony nuclei scattered over the chondroepiphysis He stated that a total absence of any osseous or cartilaginous destructive process was a feature typical of the disease

In contrast to current views Freund (1930) maintained that the fragmentation stage instead of being a destructive phase is a stage of intensive reorganization originating from the surrounding normal tissues This was confirmed by Jonsäter s (1953) histological investigations

As mentioned above the degree of fragmentation shows wide variations For this reason O Garra (1959) divided his series into two groups »anterior

Perthes disease» and »involvement of the whole epiphysis» In a series of coxa plana patients GOFF (1959) distinguished between a type with total epiphyseal involvement (37 per cent) and another type with partial epiphyseal involvement (50 per cent) The remaining patients (13 per cent) had bilateral lesions

RALSTON (1959) calculated the maximal percentage of epiphyseal involvement and studied the relationship between this parameter and various others The best correlation was noted between the extent of necrosis and the duration of the disease the larger the proportion of the epiphysis showing fragmentation the longer the duration Furthermore the investigation revealed that the smaller the portion of the epiphysis involved the more anatomical was the end result

Owing to the wide variation of the radiological changes it is very difficult to make any accurate classification of a large series on the basis of the extent of the necrosis There are of course a number of typical and obvious cases in which evaluation is easy but very often no indisputable information regarding the extent of the necrosis is obtainable from the radiographs alone JONSATER's (1953) histological investigations suggest that the necrosis is total broadly speaking

Reparative stage

In the present study radiological reparative stage is used to denominate the period from the appearance of the first signs of reossification of the fragmented epiphyseal bony nucleus until the time when the latter is uniform its structure is normalized and the epiphysis has attained its final shape

Observations on the present material In the present series the duration of the reparative stage could be evaluated in 81 cases as is shown in Table 28

TABLE 28 — *Duration of the reparative stage in 81 cases*

Duration in months	No of cases
12—24	20
24—36	27
36—48	34

Mean duration 3[illegible] months

TABLE 29 — *Relationship between duration of the reparative stage and onset age in 81 cases*

Duration of reparative stage in months	Onset age in years												Total no of cases
	2—3		4—5		6—7		8—9		10—11		12—14		
	No of cases		No of cases	%	No of cases	%	No of cases	%	No of cases	%	No of cases	%	
12—24	1	14 3	7	25 0	8	28 5	4	28 5	—		—		20
24—36	4	57 0	9	32 0	8	28 5	4	28 5	2	75 0	—		27
36—48	2	28 7	12	43 0	12	43 0	6	43 0	1	25 0	1	100 0	34

The mean duration was 32 months Table 29 demonstrates the relationship between the duration of this stage and the age at onset of the disease It is seen that almost two thirds of the cases in the lowest age group had a duration of under 36 months while almost one half in the older groups had a duration of over 36 months None of the patients who were 10 to 14 years old at the time of onset had a duration of under 24 months The different groups are too small however to allow of any definite conclusions

As a rule the first signs of reossification were seen in those areas where fragmentation began i e in the ventrolateral portion of the epiphyseal bony nucleus At this time resorption of necrotic bone tissue still occurred in other areas of the epiphysis The radiographs showed both point shaped new ossific centres in entirely demineralized areas and reconstruction of bone in the marginal areas of remaining bone fragments in which resorption had come to a standstill and regeneration had begun Occasionally diffuse homogeneous condensation was seen in entirely demineralized areas probably representing osteoid tissue which gradually undergoes mineralization Later the newformed bone substance in previously entirely decalcified areas fused with the remaining reossified fragments with the result that the ossific centre became uniform and the defects in its outline were made good As a rule the proximoventral portion of the epiphysis was ossified last An increase in breadth of the epiphysis ran parallel with its reossification

Signs of early reconstruction In 22 of the present cases radiographs taken late in the initial stage showed an osseous shadow in the chondro epiphysis lateral to the bony nucleus The primary ossific centre was still uniform although at its lateral margin the structure exhibited some rarefaction as a sign of incipient demineralization As judged from the radio graphs the above mentioned bone formation could not consist of a fragment detached from the uniform ossific centre The further radiological develop

ment clearly showed that the reformation of bone described here consisted of a fresh ossification area in the lateral portion of the chondroepiphysis the first visible sign of the formation of new bone preceding fragmentation in the bony epiphysis proper Fig 13 (case 128) illustrates this phenomenon As far as I know this early reossification phenomenon has not previously been described in the literature

Discussion of the reparative stage WALDENSTROM (1923) indicated the duration of the reparative stage as one or two years According to BRAILSFORD (1918) healing is completed during or after the fourth year counted from the onset In HELBO s (1953) series the mean duration from onset to primary healing was 52 months in untreated patients and 42 months in cases treated by protracted bed rest

In mild abortive cases reparation of the femoral epiphysis is complete Occasionally an epiphysis which has undergone slight fragmentation is rebuilt so as to become entirely symmetrical with the unaffected side The present series contained only a few such cases BRAILSFORD (1918) HELBO

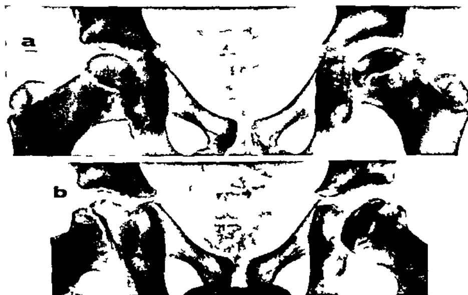


Fig 13 Case 128 boy aged 6 at onset Limping for three months before the first examination *a* frontal and *b* lateral view Coxa plana on the left side initial stage with moderate flattening and condensation of the epiphysis A broad band shaped translucent area across the metaphysis in the frontal view A large furrow shaped defect in the proximal surface of the metaphysis close to the ventral margin in the lateral view Note the large ossification area laterally in the chondroepiphysis before the bony epiphysis shows fragmentation

(1953) GOFF (1954) and others have described complete radiological healing

In the majority of cases with good end results a slight reduction in height and increase in breadth of the epiphysis occur In most cases of coxa plana broadening of the epiphysis is one of the most typical features For this reason BERGSTRAND & NORMAN (1961) suggested that the denomination coxa plana should be replaced by coxa lata

Definitive stage

When the bony epiphysis has become uniform the defects in its outline have been filled out and its structure has been normalized the process is primarily healed and has reached its definitive stage but the femoral head *still increases in size throughout the normal growing period How much the*

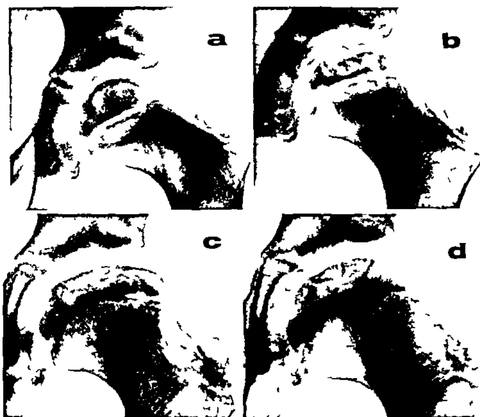


Fig 14 Case 229 boy aged 6 years and 6 months at onset The radiographs *a—d* show the development of osteochondrosis dissecans

head will grow during the definitive stage depends of course on the age at which this stage is attained

The final shape of the head shows wide variations depending on the course of the disease process The range of this variation is best illustrated by the large number of different denominations by which different authors have described the ultimate shape spherical ball formed ovoid or oval elliptical mushroom shaped cylindrical quadrangular or pyramid shaped

In the present series *the mean duration of the process of the disease was four years and four months as counted from the onset of the illness until primary healing had taken place*

In some cases the result of the reparative process was not a uniform head but one where one or more loose fragments remained in the proximal portion of the epiphysis (Fig 14)

CHANGES IN THE METAPHYSIS AND THE EPIPHYSEAL PLATE

Earlier investigations

Radiological changes In his first paper on coxa plana LEGG described radiological changes in the metaphysis which he interpreted as necrotic

Osteoporosis revealed by focal or band shaped translucent areas in an early stage of the disease have been described by WALDENSTROM (1910 1923) PERTHES (1913) SCHWARZ (1914) BRETHMANN (1914) GAGE (1933) GILL (1940) WIRZ (1953) GOFF (1954) CAFFEY (1961) and others

GILL maintained that the metaphysis is the primary site of the process the necrosis of the epiphysis being secondary

BERGSTRAND (1961) described a local marginal decalcifying process (»Lsurierung») in the proximal surface of the metaphysis preceding fragmentation of the epiphysis This change he interpreted as the first visible sign of granulation tissue invading the epiphyseal bony nucleus

MINDELL & SHERMAN (1951) were able to follow the metaphyseal changes in 53 cases The usual change consisted of a diffuse irregular zone of decreased density which sometimes appeared early and sometimes late This defect was filled in as the head of the femur healed From their observations the authors concluded that extensive changes in the femoral neck generally indicate a poor prognosis They found that the metaphyseal changes led to asymmetrical and retarded growth or epiphyseal arrest

Changes resembling those described by MINDELL & SHERMAN were also reported by GOFF (1951)

spicuous there Occasionally this defect was circular and involved the whole periphery of the metaphyseal surface In such cases the central portion of the latter formed a plateau shaped elevation surrounded by depressions An extreme example of this is shown in Fig 15 (case 14)

During the further course the cases exhibiting a furrow shaped depression in the metaphyseal surface showed a defect of the metaphyseal margin

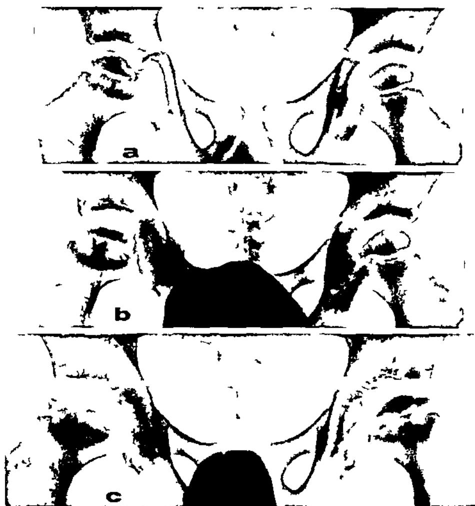


Fig 7 Case 14 boy aged 4 at onset The radiographs demonstrate severe symmetrical metaphyseal changes with circular defects in the periphery of the proximal metaphyseal surfaces and plateau shaped elevations in the central portions of the latter Total necrosis of the epiphysis *a* 6 months after onset *b* 10 months after onset *c* 23 months after onset Treated at first with Thomas splint on the right side then by bed rest for one and a half year and finally with Thomas splint on the left side End result elliptical head on both sides

leading to the development of a gap in the ventral portion of the epiphyseal plate The picture resembled that seen in the group of cases primarily exhibiting a gap (It is possible that the development of a gap in this group had been preceded by a stage in which a furrow shaped depression in the proximal metaphyseal plane occurred) During the fragmentation stage the defect in the metaphyseal margin was enlarged and gradually developed into an oblique or most often a step-shaped defect (Fig 1) The cause of this seemed to be that ossification in the central portion of the metaphysis continued while the growth in the area of the defect was arrested The margins of the step shaped defect were gradually rounded off and at the same time the whole outline of the metaphyseal surface became irregular During the later course the metaphyseal surface invariably developed a proximally directed convexity

During the reparative stage the metaphyseal defect was made good in the majority of cases in such a way that the bony epiphysis grew in the distal direction towards the defect which was thus filled out by the epiphysis Frequently isolated ossific centres were seen within the metaphyseal defect Gradually these fused with the ingrowing epiphysis As a natural result of this series of events the epiphyseal line assumed a more or less marked step-shaped irregularity in its ventro-lateral part (Fig 21)

In 3 of the cases with severe metaphyseal changes the metaphyseal defect disappeared owing to reformation of bone at its margins so that the metaphyseal surface was levelled and the epiphyseal line became regular although with a proximally directed convexity (Fig 16 case 46)

Even in areas which on the radiograph did not show any metaphyseal defect proper a tendency of the epiphysis to grow out over the metaphyseal margin was discernible with broadening of the epiphysis resulting This increase in breadth was often most conspicuous in the lateral portion in which an outgrowth of the epiphysis extending far over the femoral neck even to the greater trochanter could be seen This observation seems to indicate that there were metaphyseal changes also in other parts of the metaphyseal margin although these were not visible on the radiographs

In parallel with the ossification of the metaphyseal defect *an increase in breadth of the metaphysis occurred* Periosteal apposition of bone was a relatively frequent finding at the borderline between the metaphysis and the femoral neck usually cranially to the latter

Towards the end of the reparative stage typical deformations in the meta-epiphyseal borderline area occurred

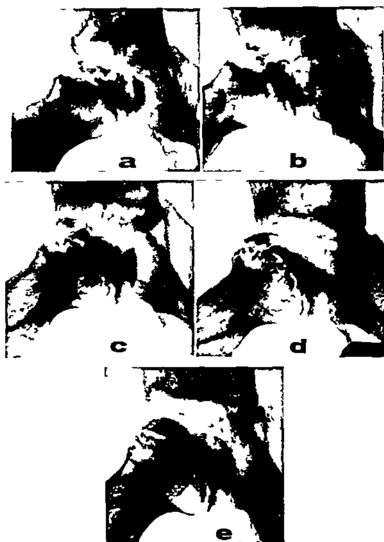


Fig 16 a—e

Normally the distal surface of the femoral epiphysis and the proximal surface of the metaphysis are almost straight Between these the epiphyseal plate is situated appearing on the radiographs like a line or a band shaped space between the epiphysis and the metaphysis

In the great majority of cases in the present series various degrees of irregularity of the proximal surface of the metaphysis were observable

As has already been mentioned the metaphyseal surface was convex in the proximal direction The convexity sometimes had a smooth outline and

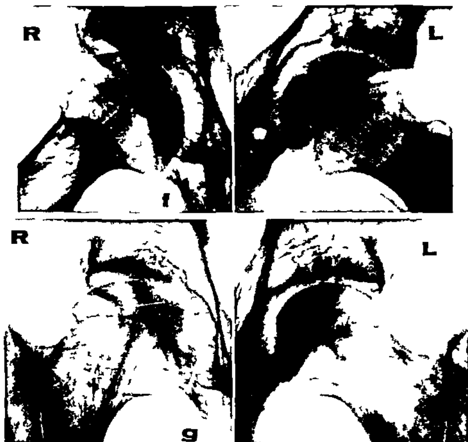


Fig 16 Case 46 boy aged 6 years and 10 months at onset A large oblique metaphyseal defect seen in *a* and *b* disappeared owing to reformation of bone at its margins as seen in *c*—*e* The epiphyseal line became regular The radiographs *a*—*e* were taken from 10 to 31 months after onset at intervals of 4 to 12 months *f* and *g* about 10 years after onset Treatment Thomas splint for 2 years and 9 months End result good

sometimes showed a more or less regular undulation or the contour was entirely irregular with deep distally directed depressions and proximally directed plateau shaped or step-shaped elevations The depressions were situated peripherally and corresponded to the primary marginal defects while the elevations were more centrally located

Often the routine radiographs did not provide an accurate concept of the changes described here Tomograms were very informative and on these the grave deformation of the metaphyseal surface was often striking (Fig 17 case 262)



Fig 17 a—c

The remodelling process in the metaphysis took place in parallel with the reparative process in the epiphysis On inspection of the large number of radiographs on which this study is based it was clearly seen that the two processes were dependent on each other but it was impossible to distinguish between cause and effect In cases where fragmentation had been slight or a coherent layer of spongy bone developed relatively soon upon the metaphyseal surface the deformation of the metaphysis was slighter Relatively marked irregularity of the metaphyseal surface was usually associated with a high degree of fragmentation and slow consolidation of the epiphysis In many cases the radiographs conveyed the impression that

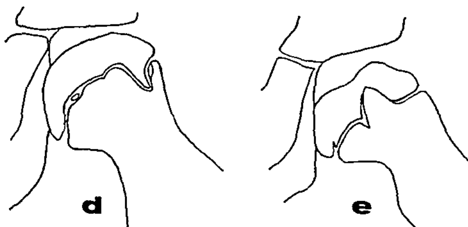


Fig 17 Case 262 boy aged 6 years at onset *a* routine radiograph *b* and *c* tomograms with a 1 cm level distance 5 years after onset Late reparative stage *d* and *e* drawings to *b* and *c* Routine radiographs do not provide an accurate idea of the changes in the meta epiphyseal borderline Tomograms give very good information regarding irregularities in the metaphyseal surface

the elevated central portion of the metaphysis intervened with the fusion of the ossifying epiphyseal fragments which was slow in this site In some cases months and years elapsed before fusion of the epiphysis occurred in this area and as a rule the layer of bone remained very thin and it seldom exhibited a normal structure (Fig 18)

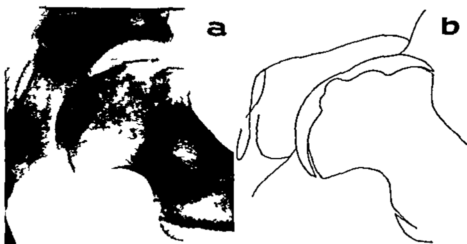


Fig 18 Case 212 boy aged 8 at onset *a* 11 years after onset *b* drawing to *a* The subcapital epiphyseal line is partially closed The metaphyseal surface is very irregular with a central elevation In the proximal part of the epiphysis the layer of bone tissue is thin and the bone structure is still irregular Untreated case



Fig 17 a—c

The remodelling process in the metaphysis took place in parallel with the *reparative process in the epiphysis On inspection of the large number of* radiographs on which this study is based it was clearly seen that the two processes were dependent on each other but it was impossible to distinguish between cause and effect In cases where fragmentation had been slight or a coherent layer of spongy bone developed relatively soon upon the metaphyseal surface the deformation of the metaphysis was slighter Relatively marked irregularity of the metaphyseal surface was usually associated with a high degree of fragmentation and slow consolidation of the epiphysis In many cases the radiographs conveyed the impression that

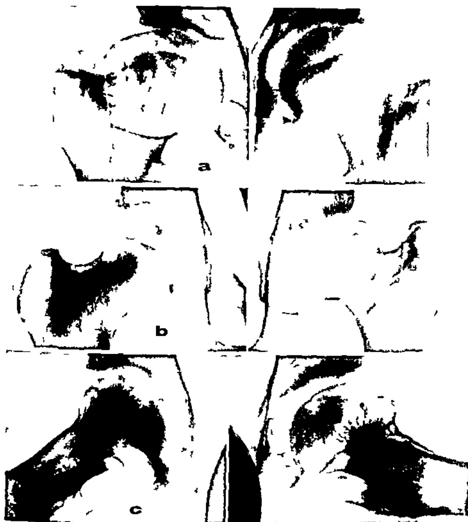


Fig 20 Examples of asymmetrical growth owing to premature fusion of the epiphyseal line *a* valgus position of the femoral head after fusion of the lateral part of the epiphyseal line *b* varus position of the head as a result of premature fusion in the medial part of the epiphyseal line *c* increased antetorsion of the head owing to fusion of the anterior part of the epiphyseal line

this case closed earlier on the ventral side (Fig 20 c) Retrotorsion was not seen in any cases

In order to enable evaluation of the relationship between premature closure of the subcapital epiphyseal line and the final shape of the femoral head the present ultimately healed cases of unilateral coxa plana were

divided into two groups depending on whether the serial radiographs revealed premature or normal closure of the epiphyseal line

In this paper premature closure stands for fusion that had certainly taken place at least one year earlier on the affected side than on the unaffected side Normal closure means that fusion occurred less than a year earlier on the affected side

The group with premature closure comprises 12 cases the group with normal closure 20 cases (Both groups were certainly larger but owing to long intervals between the examinations radiological evidence is lacking)

Table 30 shows the relationship between fusion of the epiphyseal line and the ultimate shape of the femoral head It appears in the table that in more than half the cases premature closure of the subcapital epiphyseal line was associated with poor healing of the femoral head In the group with normal closure the 2 cases which did not heal with a spherical femoral head developed a condition resembling osteochondrosis dissecans

TABLE 30 — *Relationship between closure of the subcapital epiphyseal line and ultimate shape of the femoral head*

Closure of the epiphyseal line	Shape of the femoral head			Total
	Spherical No of cases	Elliptical No of cases	Irregular No of cases	
Normal	18	—	2	20
Premature	5	13	4	12

From the standpoint of the end result in the femoral head premature closure of the epiphyseal line thus seems to be an unfavourable sign

For the sake of evaluating the relationship between the metaphyseal changes and the closure of the subcapital epiphyseal line the ultimately healed cases were classified according to the degree of metaphyseal changes *The classification was made at a late reparative stage* as close as possible to the time of epiphyseal fusion The following principles of classification were used

Small or no changes the proximal surface of the metaphysis plane or regularly convex

Moderate changes step shaped marginal metaphyseal defect filled up by the epiphysis otherwise a regularly convex metaphyseal surface

Marked changes metaphyseal surface very irregular the central portion plateau shaped and elevated

The increase in breadth of the metaphysis as compared with the unaffected side was measured in the lateral view while the shortening of the femoral neck was measured in the frontal view.

The relevant observations are listed in Table 31 which shows that premature closure of the epiphyseal line in most cases was associated with marked metaphyseal changes. In cases with normal closure the metaphyseal changes as a rule were slight. The increase in breadth of the metaphysis and the decrease in length of the femoral neck were clearly larger in the cases showing premature closure than in those showing normal closure.

TABLE 31. — *Degree of metaphyseal changes, broadening of the metaphysis and shortening of the femoral neck in 4[illegible] unilateral ultimately healed cases with premature closure and [illegible]0 cases with normal closure of the subcapital epiphyseal line*

Closure of the epiphyseal line	Degree of metaphyseal changes			Broadening of the metaphysis in mm mean (range)	Shortening of the femoral neck in mm mean (range)
	Slight No of cases	Moderate No of cases	Severe No of cases		
Premature	3	5	34	12 (3—23)	17 (0—30)
Normal	16	4	—	4.3 (0—9)	4.5 (0—9)

It may be concluded that marked metaphyseal changes and marked broadening of the metaphysis and retardation of the longitudinal growth of the femoral neck are unfavourable prognostic signs indicating that the epiphysis will close prematurely.

Fig. 21 (case 218) shows the radiological course in a girl who was 7 years old at the onset of coxa plana. This case represents moderate metaphyseal changes.

Discussion

The present observations concerning the *metaphyseal changes and premature closure of the subcapital epiphyseal line* agree well with the above mentioned reports of MINDELL & SHERMAN, GOFF and EVANS. With regard to the ossification of the metaphyseal defect there is a high degree of correspondence between the observations made in the present series and those of MOSE.

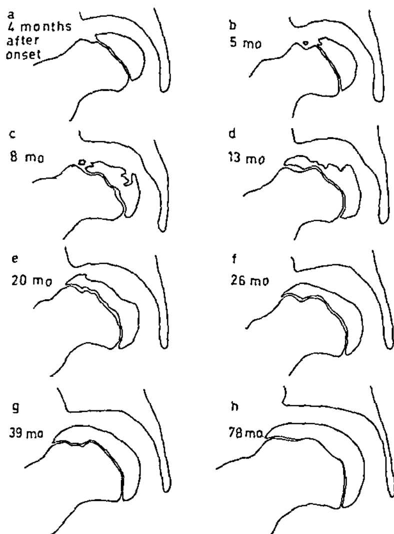


Fig 1 Drawing based on lateral radiographs of the right hip showing the radiological course of coxa plana in a girl aged 7 years at onset of the disease (case 248) *a* 4 months after onset the epiphysis is slightly flattened in the ventral margin of the metaphysis there is an oblique defect *b* 5 months after onset fragmentation in the ventral part of the epiphysis a step shaped defect in the ventral margin of the metaphysis there is a small ossification centre in the metaphyseal defect *c* 8 months after onset fragmentation proximally in the epiphysis the ventral part of the epiphysis is growing into the metaphyseal defect the margins of the defect are rounded the ossification centre in the defect is enlarged thickening of the periosteum ventrally on the neck *d* increased demineralization proximally in the epiphysis the ossification centre in the metaphyseal defect is fused with the ventral part of the epiphysis which fills up the defect the metaphysis is broadened *e*—*g* mineralization of the epiphysis proceeding the borderline of the metaphyseal defect is still visible the epiphyseal line is slightly wave like *h* 78 months after onset the central part of the epiphyseal line is closed

The premature fusion of the subcapital epiphyseal line may begin in different areas of the growth zone This accounts for the deviations from the normal relationship between the positions of the femoral head and neck seen in coxa plana and it also explains the conflicting conclusions drawn by certain previous authors regarding the final deformation in this disease Thus LEVY (1911) for instance described cases in which the femoral head occupied a varus position in relation to the neck and suggested that the name of the condition osteoarthritis deformans coxae juvenilis should be substituted by »coxa vara capitalis» DREHMANN (1914) on the other hand reported cases with a valgus position of the femoral head in relation to the neck and suggested the denomination »coxa valga epiphysaria»

Analogous deformities following partial epiphyseal closure are known from other skeletal diseases In tibia vara for instance premature closure of the medial portion of the proximal epiphyseal line of the tibia is a common phenomenon and leads to a marked increase of the varus deformity (A LANGENSKIOLD 1952)

The degree of the deformity under discussion is of course entirely dependent on how long the growth continues and how rapid it is in still functional parts of the growth zone after partial fusion of the epiphyseal line has taken place

Thickening of the metaphysis The cause of the increase in breadth of the metaphysis has been discussed by many authors BERNBECK (1934) regarded this broadening in part as initial apposition of osseous lamellae caused by the irritation resulting from overgrowth of the epiphysis over the metaphyseal border in part as appositional increase in thickness implying strengthening of weak osseous parts

HELBO (1954) who — like many other authors — observed periosteal apposition in the lateral surface of the femoral neck accorded no major significance to this phenomenon from the standpoint of the thickening of the femoral neck He observed the same periosteal reaction in an early stage in patients who later exhibited good end results without any thickening of the neck of the femur HELBO regarded the metaphyseal changes and weight-bearing as responsible for the increase in breadth

In the present series there are cases in which periosteal apposition undoubtedly seemed to contribute to the increase in breadth of the femoral neck but in the great majority of cases no such reaction of the periosteum was observable As evaluated on the basis of the radiographs the thickening of the femoral neck was obviously due to growth phenomena in the metaphysis which is the region where the increase in breadth appears first and is most conspicuous

An increase in volume of the proximal end of the femur is relatively frequent after reduction of congenital luxation of the hip, and also occurs in cases where no radiological signs of epiphyseal necrosis are observable Such a coxa magna is attributed to local growth stimulating phenomena possibly elicited by the reposition trauma

It seems probable that similar stimulating factors also play a part in coxa plana

Formation of a step in the metaphysis A Langenskiold (1952) described the radiological changes in the infantile type of tibia vara (osteochondrosis deformans tibiae) Some cases exhibited a defect in the proximal meta physis of the tibia causing a definite step The defect was attributed to growth arrest in one portion of the metaphysis and continued ossification in the remainder The step shaped defect was filled out by a broadened part of the epiphyseal cartilage and in a later stage it was found to be occupied by the bony epiphysis (Fig 22)

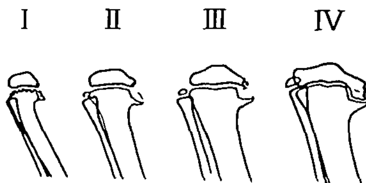


Fig Formation of a step shaped metaphyseal defect in tibia vara Compensatory epiphyseal growth the defect is occupied by the bony epiphysis (According to A Langenskiold 1952)

By mechanical injury to the proximal tibial growth cartilage in rabbits A Langenskiold (1955) provoked changes resembling those seen in tibia vara *i e* a metaphyseal depression compensatory growth of the epiphysis and a varus deformity (Fig 23)

Metaphyseal defects associated with osteomyelitis and tuberculosis in children are relatively frequent A Langenskiold (1955) has described compensatory epiphyseal filling of these defects and emphasized the resem blance between this regenerative process and that observed by him in tibia vara (Fig 24)

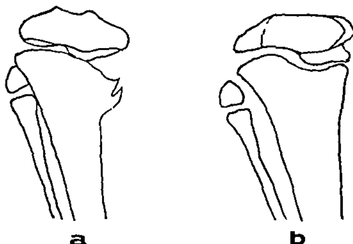


Fig 23 *a* drawing of a radiograph of the tibia of a young rabbit taken 10 days after removal of the medial part of the zone of cartilage cell columns from the proximal epiphyseal plate There is an oblique defect in the metaphysis *b* drawing of a radiograph of the upper end of the tibia of a rabbit taken 16 days after removal of the medial part of the zone of cartilage cell columns from the epiphyseal plate The metaphyseal defect is occupied by an extension of the bony epiphysis (According to A LANGENSKIÖLD 1954)



Fig 24 A tomogram of a patient aged 7 years and 3 months The steplike deformity had developed in the distal growth zone of the femur after osteomyelitis in infancy Compare with *Fig* 17 *b* The resemblance of the changes is striking (Reproduced by courtesy of LANGENSKIÖLD & RISKA and the *J Bone & Joint Surg* Am 1964)

VIII THE GREATER TROCHANTER

Earlier observations

In his paper of 1913 PERTHES pointed out that the greater trochanter was strikingly large in some of his cases Similar observations were reported by ANHAUSEN (1923) These authors attributed the hypertrophy to proliferative phenomena around the greater trochanter BIBERGEIL (1912) who also noted that the trochanter was large correlated this finding with atrophy of the femoral head and neck

SUNDT (1920) described in his monograph some cases of coxa plana with hypertrophy of the greater trochanter Since in some of these the trochanter was also hypertrophic on the unaffected side he drew the conclusion that the hypertrophy had no connexion with the disease process in coxa plana

In his paper called »The definite form of the Coxa plana» WALDENSTRÖM (1922) described the radiological picture in his end result group 3 as follows »The upper pole of the caput is edgeformed and usually lower than the summit of the greater trochanter» but he offered no explanation of this observation

CAVA (1924) also discussed this phenomenon without being able to trace its cause

PERTTILA (1954) reported that in 10 out of 33 patients with coxa plana who were followed up the tip of the greater trochanter was situated more cranially than the proximal pole of the femoral head The elevation of the tip of the greater trochanter was not accounted for

GOFF (1954) and HORWITZ (1960) published radiographs of elevated greater trochanters but did not discuss the cause of the elevation

Observations on the present material

In the present series no radiological changes indicative of necrosis were observable in the greater trochanter

As appeared in the foregoing retardation of the longitudinal growth of the femoral neck and premature closure of the subcapital epiphyseal line

are of frequent occurrence in coxa plana As a rule the growth of the greater trochanter was not affected by the process Since the longitudinal growth of the femoral neck may cease completely at the age of 12 to 14 years while the growth of the greater trochanter continues until the age of 17 to 18 years and sometimes longer it is obvious that a discrepancy between the femoral head and neck on the one hand and the greater trochanter on the other must result On the radiographs this was discernible as a reduction of the distance between the tip of the greater trochanter and the proximal pole of the femoral head In the present paper this distance is called the *articulo-trochanteric distance*

For the sake of assessing the influence of the process of the disease in coxa plana on the articulo-trochanteric distance measurements were made on the radiographs For this purpose perpendiculars were drawn against the longitudinal axis of the femoral diaphysis so as to touch the proximal pole of the femoral head and the tip of the greater trochanter The distance between these perpendiculars was measured in millimetres In what follows it is denominated ATD (Fig 26) If the tip of the greater trochanter was situated distally of the proximal aspect of the femoral head the ATD was regarded as positive It was regarded as negative when the tip of the greater trochanter was situated proximally of the proximal aspect of the head of the femur

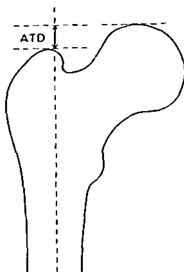


Fig 26 Determination of the articulo trochanteric distance ATD

In order to find out to what extent the ATD is influenced by different rotational positions of the femur frontal radiographs were taken of 12 hip joints in the neutral position and in 20 degrees outward and inward rotation The radiographs were taken by the same technique as was used in examining the coxa plana patients In addition a specimen was radiographed in the same way As compared with the neutral position the ATD was found to increase on outward rotation and decrease on inward rotation The results of these tests are shown in Table 32 Although the differences were small they may have influenced the measurements in the present series to some degree *The errors were reduced however by the radiographic* technique which was elaborated so as to attain the greatest possible degree of standardization of the projections The severest deformities involving the largest reductions of the ATD were often associated with a slight outward rotation of the extremity and a limitation of the 20 degrees inward rotation which is a condition of our standard technique The readings for the ATD therefore represent maximum values

TABLE 32 — *ATD in 12 normal hip joints and in a specimen in the neutral position outward rotation and inward rotation*

	Articulo trochanteric distance	
	Mean in 12 normal hips mm	Specimen mm
Neutral position	21	18
Outward rotation	24	20
Inward rotation	19	14

The results obtained after the completion of growth in 81 unilateral cases of coxa plana are shown in Table 33

TABLE 33 — *ATD in unilateral coxa plana after completion of growth in relation to shape of the femoral head*

Shape of the femoral head	Articulo trochanteric distance				
	Affected hips		Unaffected hips		No of cases
	Mean	(Range)	Mean	(Range)	
Spherical	11.7	(+21— — 9)	16.0	(+24— + 6)	23
Elliptical	1.7	(+13— — 4)	15.9	(+28— +11)	17
Irregular	2.2	(+17— —19)	15.1	(+28— + 8)	41

The results obtained in the same group at an earlier stage of the disease before closure of the subcapital epiphyseal line are shown in Table 34

Table 35 shows the results of measurement after the completion of growth in 20 bilateral cases of coxa plana

From Tables 33 and 34 it appears that no reduction of the ATD was primarily present (it occurred at a late reparative stage in part only when the femoral head had attained its final shape) The reduction of the ATD increased with poorer end results in the head although it was sometimes marked also in cases healing with a spherical head

TABLE 34

Shape of the femoral head	Articulo trochanteric distance			
	Affected hips		Unaffected hips	
	Mean	(Range)	Mean	(Range)
Spherical	17 2	(+24— + 5)	16 8	(−2(— − 8)
Elliptical	14 8	(+18— +12)	16 9	(+22— −12)
Irregular	14 1	(+2(— + 5)	16 4	(+30— + 8)

TABLE 35 — *ATD in relation to ultimate shape of the femoral head after completion of growth in 0 cases of bilateral coxa plana*

Shape of the femoral head	Articulo trochanteric distance		No of hips
	Mean	(Range)	
Spherical	10	(+18— — 3)	13
Elliptical	8 8	(−15— − 1)	4
Irregular	0 9	(+26— —19)	23

In Table 36 the ATD in the group with unilateral coxa plana showing premature closure of the epiphyseal line is compared with the ATD in the group showing normal closure It is seen in the table that the ATD was markedly reduced in the group showing premature closure In the group showing normal closure the reduction of the ATD was slight as compared with the unaffected side Fig 27 shows the results of measurement of the ATD in these groups

TABLE 36 — *ATD in unilateral ultimately healed coxa plana with premature closur (42 cases) and normal closure (20 cases) of the subcapital epiphyseal line*

Closure of the epiphyseal line	Articulo trochanteric distance				No of hips
	Affected hips		Unaffected hips		
	Mean	Range	Mean	Range	
Premature	1 3	+13— —11	16 2	+28— +5	42
Normal	13 7	+23— + 5	15 4	+21— +6	20

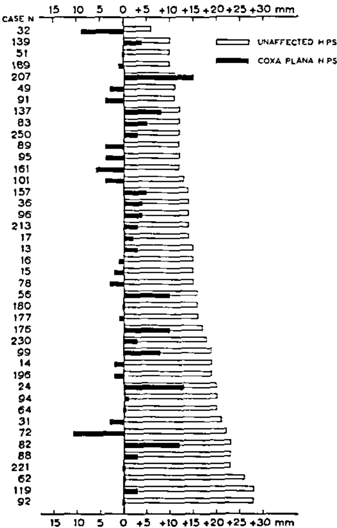


Fig a

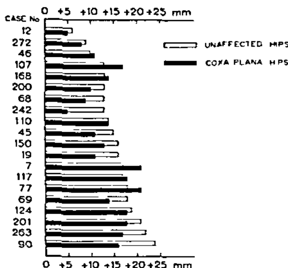


Fig 7 b

Fig 7 *a* the articulo-trochanteric distance in 42 cases showing premature closure of the epiphyseal line and *b* in 20 cases showing normal closure of the epiphyseal line

Case 230 in the present series is a typical example of reduction of the ATD in connexion with premature closure of the subcapital epiphyseal line The essential data are listed in Table 37

The series includes 7 cases in which the radiographs were indicative of premature and simultaneous closure of the subcapital growth line and the growth line of the greater trochanter In these cases 5 of which healed

TABLE 37 — *Reduction of ATD in a typical case of coxa plana Case 30 Boy aged 8 at onset in Sept 1957 Right side affected*

Date	Right hip Condition of the epiph lines		ATD		Left hip Condition of the epiph lines	
	Subtro-chanteric	Subcapital	Right	Left	Subcapital	Subtro-chanteric
April 1959	Open	Open (Reparat st)	+ 15	+ 16	Open	Open
April 1960		Very irregular	+ 14	+ 15		
Oct 1960		Partly closed	+ 12	+ 16		
April 1961		More closed	+ 10	+ 15		•
Oct 1961		Almost closed	+ 8	+ 17	•	•
Oct 1962		Closed	+ 3	+ 18	Partly closed	•
Jan 1964	Closed		+ 3	+ 18	Closed	Closed



Fig 8 a—b

with irregular femoral heads 1 with an elliptical and 1 with a spherical femoral head no major reduction of the ATD occurred On the affected side this distance was a mean of 14 6 mm (the range being from +9 to +26 mm) and on the unaffected side a mean of 15 9 mm (the range being from +7 to + 25 mm) In some of these cases the premature closure of the epiphyseal line of the greater trochanter was apparently due to the epiphysis having grown out over the cranial aspect of the femoral neck so as to come into contact with the trochanter at its base close to the epiphyseal line It may be assumed that vascular anastomoses between the epiphysis of the trochanter and the metaphysis had been established with fusion of the growth line resulting in the same way as in the subcapital region In some cases this mechanism was obviously not responsible however and the radiographs afford no explanation of the premature closure of the growth line of the greater trochanter

From the observations made in the present series concerning the growth of the proximal part of the femur the conclusion may be drawn that *the*

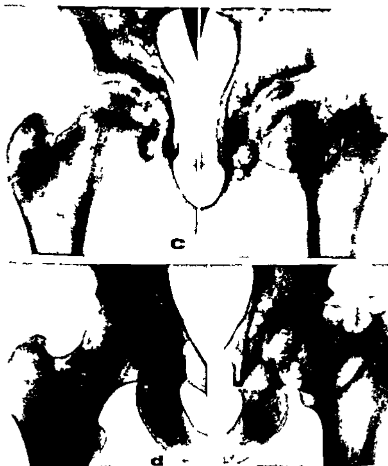


Fig 28 Case 161 girl aged 7 years at onset Treated for 9 months with Thomas splint in an advanced stage of the disease *a* *September 1954 late reparative stage the epiphyseal line very irregular* *b* August 1956 primary healing the subcapital epiphyseal line partially closed ATD + 11 mm on the left side + 16 mm on the right side Trendelenburg's sign negative *c* October 1959 the subcapital epiphyseal line closed the subtrochanteric epiphyseal line still open ATD left — 3 mm right + 12 mm Trendelenburg's sign positive to the left *d* February 1963 all growth lines closed ATD left — 6 mm right + 12 mm The left femoral head slightly irregular enlarged Normal mobility in the left hip Trendelenburg's sign positive

elevation of the greater trochanter in coxa plana is due to retardation of the longitudinal growth of the femoral neck and premature closure of the subcapital epiphyseal line while the growth of the greater trochanter proceeds as normal throughout the remainder of the growing period

Fig 28 (case 161) illustrates the elevation of the greater trochanter associated with premature closure of the subcapital epiphyseal line

IX THE DEFORMITY IN COXA PLANA

VARUS OR VALGUS

Earlier observations According to HOFMEISTER's (1894) definition coxa vara is present if the neck-shaft angle is smaller than normal (120 degrees in adults v LANZ-WACHSMUTH 1938) This definition does not take the greater trochanter into account which is an integrating part of the proximal end of the femur and derives its epiphyseal plate from the same preplate as the femoral head (see p 23) SOURDAT (1909) and CALVE (1910) stated that coxa plana leads to a varus deformity WALDENSTROM (1910) who observed no appreciable alteration of the neck shaft angle in coxa plana did not regard the deformity caused by the disease as a varus deformity but he pointed out that an apparent varus deformity may result if the medial portion of the femoral head grows in the medio caudal direction Many other authors have adopted the same view e g HORWITZ (1960) and LEGER (1961) The latter wrote »Die Perthesche Erkrankung ist zu der durch Wachstums storungen bedingten Coxa vara im engeren Sinne nicht zu rechnen» GORFF (1954) reported that he had not observed any varus deformity in his series except in the group »irregular type» in which no coxa vara was present at first but sometimes developed soon enough as an osteomalacia of a local character

SUNDT (1949) measured the neck shaft angle on the radiographs taken at follow up investigation of his series He found that the angle was almost invariably enlarged and concluded »The disease has thus an unmistakeable tendency to produce a valgus position of the neck »

PERTTILA (1951) too measured the neck shaft angle and found that the coxa valga type was clearly prevalent when the determinations were made on neutral position radiographs He emphasized however that the values obtained by this method were too high It seems probable that the large neck shaft angles noted by SUNDT were also due to the fact that the measure ments were made on radiographs taken in the neutral position or possibly in outward rotation

PERTTILA regarded functional coxa vara as being present in those cases where the greater trochanter is elevated

EVANS (1958) determined the neck shaft angle in a series of 52 patients A valgus deformity was present in 6 cases in which the angle was increased by over 10 degrees as compared with the unaffected side In no case was any marked varus deformity noted The author pointed out that marked shortening of the head neck segment is shown clinically by elevation of the greater trochanter

In the present series no major changes of the neck shaft angle were observed The measurements were made on radiographs taken in 20 degrees inward rotation

LANGENSKIOLD & SARPIO (unpublished) and LAURENT (1959) showed in animal experiments LAURENT (1959) and PYLKKANEN (1960) in clinical series that a coxa vara deformity developed when the activity of the subcapital epiphyseal plate was disturbed or prematurely came to a standstill while a coxa valga deformity resulted when the activity of the epiphyseal plate of the greater trochanter was disturbed or prematurely ceased

Discussion In the *distal end of the femur* the epiphysis consists of two condyles originating from a common growth plate If the growth process is inhibited in the growth zone of the medial condyle while the lateral condyle continues to grow a varus deformity develops *Vice versa* if the growth of the lateral condyle is inhibited a valgus deformity results

In certain mammals *e g* the elephant the preplate is not differentiated into a separate epiphyseal plate for the femoral head and another for the greater trochanter The head and the trochanter grow from the same growth plate (LUTKEN 1961) In rare cases a bony bridge is formed between the capital epiphysis and the bony nucleus of the trochanter in man so that a common uniform epiphyseal plate for the femoral head and the greater trochanter develops LUTKEN described 3 such cases and MAU (1962) also described 3 At the Orthopaedic Hospital of the Invalid Foundation I have observed 2 such cases in which the formation here described developed after closed reduction of a congenital hip luxation (Fig 29) In such cases similar conditions prevail in the proximal and distal ends of the femur which justifies a comparison of these structures The head and the greater trochanter may be compared with the two condyles If the growth of the medial subcapital region is arrested while the lateral trochanteric area continues to grow a varus deformity develops and *vice versa* if the growth of the trochanteric region is arrested while the subcapital region continues to grow a valgus deformity results

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X TRENDELENBURG's SIGN

Earlier investigations

The greater trochanter is the site of insertion of the abductors of the femur in the first place the gluteus medius and gluteus minimus From the stand point of the function of the pelvitrochanteric abductor muscles and the statics in the pelvic hip region the position of the greater trochanter in relation to the pelvis is of fundamental importance In the presence of a coxa vara deformity e g in coxa vara infantum the function of the pelvitrochanteric abductors is impaired owing to elevation of the greater trochanter The abductor insufficiency is manifested by a positive Trendelenburg sign (v Lanz Wachsmuth 1938 Pylkkanen 1960)

Limping is a constant early symptom in coxa plana This form of limp was described by Calvi *et al* (1939) as »antalgic gait» and it differs from Trendelenburg s type At the time of primary healing the limp if there is any is of a neutral type due to shortening of the limb (Calve *et al* 1939 Goff 1954) If the disease leads to a varus deformity i e if the greater trochanter is elevated in relation to the hip joint and if abductor insufficiency develops the limp is of Trendelenburg s type

Observations on the present material

In the present series a positive Trendelenburg sign was noted in 26 cases of ultimately healed unilateral coxa plana In 15 of these the ATD was 0 or negative *ad* — 9 mm In 9 cases the ATD varied between + 1 and — 5 mm In 1 case the ATD was + 8 mm in the coxa plana hip against + 23 mm in the unaffected hip which implies a marked reduction In 1 case no appreciable reduction of the ATD was demonstrable (+ 12 mm against + 13 mm in the unaffected hip) In this case the positive Trendelenburg sign must be attributed to some other cause than reduction of the ATD probably to muscular insufficiency

Among the 26 cases with positive Trendelenburg signs there were 9 in which a retrospective examination of the clinical data and the radiographs

revealed that Trendelenburg's sign had been negative at a late reparative stage of the disease and that no or only a slight reduction of the ATD had then been present (Fig 28)

As far as the shape of the femoral head is concerned the radiological end results were mostly poor in this group Two cases healed with spherical heads 7 with elliptical and 17 with irregular heads

The present observations in the cases with positive Trendelenburg signs show that *abductor insufficiency in coxa plana may develop at a very advanced stage of the disease as a result of elevation of the greater trochanter*

XI PREVENTION OF DEFORMITY BY EPIPHYSIODESIS OF THE GREATER TROCHANTER

In 1961 epiphysiodesis of the greater trochanter was performed at the Orthopaedic Hospital of the Invalid Foundation in 3 cases of coxa plana In 2 of these the ATD was markedly reduced at the time of the operation i e + 2 and — 1 mm in the affected hips against + 12 and + 1 mm on the unaffected side In the latter case moderate bilateral coxa vara was already present at the time of the diagnosis The deformity was probably due to rickets In the third case epiphysiodesis was performed at a late reparative stage On the affected side the subcapital epiphyseal line was partially closed but the ATD was not reduced it was + 12 mm on both sides The operation was performed by Phemister s (1933) method first applied to the greater trochanter by A Langenskiold in 1957 (personal communication)

On follow up examination of these patients 17 22 and 11 months respectively after operation the growth line of the greater trochanter was found to be closed in all cases In the first two cases the reduction of the ATD had increased by 2 mm on the side operated upon and was thus 0 and — 6 mm respectively Trendelenburg s sign was in these cases weakly positive In the *third case the ATD had been enlarged by 1 mm and was + 13 mm on both* sides Trendelenburg s sign was negative

During the years 1963 and 1961 epiphysiodesis of the greater trochanter was performed in 20 unilateral and 2 bilateral cases of coxa plana in which radiological studies revealed progressive reduction of the ATD or premature closure of the subcapital epiphyseal line Thirteen of these cases do not belong to the present series

In Table 38 the principal data regarding the patients operated upon are compiled

Discussion

It appears from Table 36 that the reduction of the ATD was arrested by epiphysiodesis *of the greater trochanter* In the cases which were followed up the postoperative reduction of the ATD was a maximum of 2 mm except in 2 cases (J K and J Y) in which the ATD had been reduced by 4 and 3 mm respectively In the bilateral case L J the ATD on the operated right side decreased by 1 mm during the time of observation while the reduction of the ATD on the non-operated left side was 13 mm during the same period In 8 cases the ATD had been enlarged by 1 mm

In all cases which have been followed up the epiphysiodesis led to partial or complete fusion of the growth line of the trochanter (Fig 31)



Fig 31 Case M L R (not in the present series) girl aged 6 years at onset *a* in June 1964 five and a half years after onset the subcapital epiphyseal line is partially closed on the affected left side ATD is + 3 mm and had decreased from + 7 mm in Dec 1962 Epiphysiodesis of the left greater trochanter was performed in June 1964 *b* Oct 1964 *The subtrochanteric epiphyseal line is closed on the left side ATD is + 1 mm on the left* side and + 8 mm on the right side as was the case at two previous examinations Trendelenburg s sign was negative

In many cases the operation was performed late when marked elevation of the greater trochanter was already present

If epiphysiodesis of the greater trochanter is performed at a favourable point of time it appears to be possible to prevent elevation of the trochanter and consequent abductor insufficiency

TABLE 38 — *Coxa plana cases in which epiphysiodesis*

Case	Year of birth	Stage of process at time of oper	Condition of epiphyseal line at time of oper		Articulo tro		
					At time of operat		Time of oper
			Subcapital	Sub trochant	Unaffected hip	Affected hip	
L M I	1947	Late repar	Part closed	Open	+12	+ 2	Oct 1961
M U	1947	Repar	•		+ 4	— 4	
N N	1947	Late repar		•	+12	+12	Nov 1961
I K	1952	Repar	Open irreg		+18	+12	Feb 1963
I J	1949	R Prim heal	Closed		—	+ 7	Mar 1963
		L			—	+16	Un oper
N T	1948	Late repar			+19	— 4	June 1963
I N	1950	Prim heal	•		+11	— 3	Oct 1963
R L	1952	Repar	Open irreg		+10	+ 1	Jan 1964
J Y	1950	Late repar			+15	+11	
I N	1952	Prim heal	Part closed	•	+22	+ 8	Feb 1964
I S	1950	Late repar	Open irreg		+14	+11	Mar 1964
A N	1949	Prim heal	Part closed		+14	+ 3	•
I M	1951	R Repar	Closed		—	0	
		L Prim heal			—	0	
P K	1953	Repar	Open irreg	•	+16	+ 2	•
I M	1953	Prim heal	Part closed		+15	+ 9	May 1964
M L R	1953	Late repar			+ 8	+ 3	June 1964
F K	1950	Prim heal	Closed		+25	+ 6	July 1964
O N	1950	Repar			+11	+ 8	
A N	1951	Late repar	Part closed	•	+17	+ 1	
N M L	1951	Prim heal			+13	+ 4	
R Y	1955	Late repar		•	+17	+12	Aug 1964
N R	1954				+14	+ 5	Sept 1964
R N	1954	Prim heal	Open irreg		+11	— 1	
I M	1955	Repar			+16	+15	Oct 1964
H S	1953				+12	+10	

of the greater trochanter was performed

chanteric distance		Condition of epiphyseal line after operation		Observation time after operation in months
After operation				
Affected hip	Unaffected hip	Subcapital	Subtrochanteric	
0	+13	Closed	Closed	17
− 6	+ 2			34
−13	+13			14
− 8	+15	•	Part closed	19
+ 6	—		Closed	15
+ 3	—		Open	15
				—
− 4	+14		Closed	11
+ 2	+ 9	Part closed	Part closed	10
+ 8	+15	•		6
+ 6	+19			10
−11	+14	Open irreg	•	12
+ 4	+15	Closed	Closed	9
+ 1	—			6
− 2	—			6
+ 3	+16	Open irreg		6
+ 8	+16	Part closed		4
+ 4	+ 8	Closed		4
+ 7	+26			3
+ 8	+11	Part closed		3
+ 1	+17	Closed		7
+ 3	+13			4
+11	+16			6
+ 4	+15	Part closed	•	8
				—
−16	+16	Open irreg		5
−10	+12			5

XIII SUMMARY

The study was carried out on a series of patients registered at the Radiological Department of the Orthopaedic Hospital of the Invalid Foundation during the years 1946—1958 The series comprised 276 cases from the whole of Finland Fifty cases being bilateral the total number of coxa plana hips was 326 The ratio of males to females was 4 1 A slight preponderance for left sided lesions was noted The youngest patient was 2 years and 8 months old the oldest 11 years at onset of the disease The highest frequency was observed in the age group 6—7 years The mean duration of symptoms at the time of diagnosis was 9 6 months Of the cases of active coxa plana 18 3 per cent were diagnosed in the initial stage

Treatment The treatment was conservative and mostly consisted of weight relief on the affected side accomplished with Thomas splint and elevation of the opposite shoe In 27 cases the treatment by Thomas splint was preceded by some weeks hospitalization during which the walking caliper was manufactured and fitted and the patient was instructed in its use A small number of patients were treated by bed rest or by non weight bearing with crutches at home The mean duration of non weight bearing was 2 3 years

End results The end results were classified into spherical head = good elliptical head = fair and irregular head = poor result In a total of 16[illegible] treated hips the result was good in 49 1 per cent fair in 21 2 per cent and poor in 29 7 per cent When end results and onset age were correlated the results were found to be clearly better in the younger age groups Furthermore it was found that the shorter the duration before the institution of treatment and the earlier the stage of the disease when treatment was instituted the better were the results

Conditions resembling *osteochondrosis dissecans* were observed in 16 hips *i e in 5 2 per cent of the hips with coxa plana examined* In 7 of these cases there was a history of trauma suggestive of a causal relationship

Aetiological factors In 3 6 per cent of the present cases the disease was preceded by a single trauma which may be considered directly related to the

development of coxa plana In 5 cases the disease was preceded by general or localized infection which may be regarded as a factor of aetiological significance Radiologically verified coxa plana was encountered in 11 close relatives of those patients numbering 172 who were particularly questioned on this point This high frequency (6 4 per cent) seems to indicate that hereditary factors play a part in the development of the disease

The course of the radiological changes In the present series the mean duration of the initial stage was 5 6 months The duration of the initial stage was independent of the onset age

The mean duration of the fragmentation stage was 10 8 months A lower onset age did not seem to shorten the duration of the fragmentation stage

The mean duration of the reparative stage was 32 months The duration of reconstruction was somewhat shorter in the younger than in the older age groups

The mean duration of the disease was 4 years and 4 months counted from the onset of illness until primary healing had taken place

In mild abortive cases no changes were detectable in the metaphysis In some cases with slight or moderate signs of fragmentation in the epiphysis slight reversible metaphyseal changes were observed During the initial stage the most frequent metaphyseal change was a band shaped zone of demineralization across the proximal portion seen on the frontal view This zone represents a defect in the ventral margin of the metaphysis seen on the lateral view (Fig 13 p 71) During the fragmentation stage the defect was enlarged and gradually developed into an oblique or most often a step shaped defect owing to the fact that the ossification of the central portion of the metaphysis continued while growth was arrested in the area of the defect (Fig 21 p 86) The metaphyseal surface developed a proximally directed convexity During the reparative stage the metaphyseal defect was filled out by the epiphysis (Fig 21) In occasional cases with severe metaphyseal changes the metaphyseal defect disappeared owing to reformation of bone at its margins In such cases the metaphyseal surface was levelled and the epiphyseal line became regular (Fig 16 p 78—79) The epiphysis showed a tendency to grow out over the metaphysis with broadening of the epiphysis resulting Parallel with the ossification of the metaphyseal defect and the epiphysis an increase in breadth of the metaphysis occurred Inhibition of the longitudinal growth of the femoral neck was observed

Various degrees of irregularity of the proximal surface of the metaphysis were observable Tomograms were very informative in this respect (Fig 17

p 80—81) Towards the end of the reparative stage the epiphyseal line became thinner Partial and gradually total fusion of the epiphyseal line often occurred earlier on the affected side than on the unaffected side As a consequence of this asymmetrical growth with malposition of the head in relation to the neck resulted in some cases (Fig 20 p 83)

Severe metaphyseal changes are often associated with poor healing of the femoral head premature closure of the subcapital epiphyseal line broadening of the metaphysis and shortening of the femoral neck

Formation of a step in the metaphysis Step shaped metaphyseal defects have previously been described in tibia vara (Fig 22 p 88) and after osteomyelitis or tuberculosis (Fig 21 p 89) of the long bones Similar metaphyseal defects have been produced in animal experiments (Fig 23 p 89) In juvenile osteochondrosis of the lumbar vertebrae ossification defects have been observed which resemble the above mentioned A feature in common to all these defects appears to be that growth is arrested locally while it continues in the surroundings Initially the metaphyseal defects are filled out by cartilage As ossification continues the metaphyseal defects are often filled out by the bony epiphysis The development of the metaphyseal defects observed in the present series of coxa plana as studied on the basis of radiographs showed a striking resemblance to the course described above

On the basis of the scanty observations previously reported concerning the histological changes of the epiphyseal plate in coxa plana and in necrosis following a fracture of the femoral neck in adolescence and on the basis of reports on extensive necrosis of the epiphyseal cartilage in connexion with experimental epiphyseal transplantation it seems obvious that necrosis of the cartilage tissue in the epiphyseal plate is a pathogenetic factor in common to the development of metaphyseal defects of the kind described here

The pathogenesis of coxa plana It is a generally accepted view that the coxa plana process is histopathologically an avascular necrosis The primary cause of the vascular disturbance is still obscure

On the basis of earlier investigations concerning the circulatory conditions in the proximal part of the femur in the coxa plana age the bony epiphysis is supplied only by the lateral epiphyseal arteries departing from the medial circumflex artery The central portion of the metaphysis is supplied by the nutrient artery the peripheral parts by the superior and inferior metaphyseal arteries which are branches of the medial circumflex artery In coxa plana the lateral epiphyseal vessels and probably the metaphyseal vessels are obstructed owing to a cause not yet established the result being

necrosis of the epiphysis and corresponding areas of the epiphyseal cartilage and the metaphysis Radiologically this is evidenced by condensation flattening and fragmentation of the epiphysis and a defect in the periphery of the metaphyseal surface The central part of the metaphysis supplied by the nutrient artery continues to grow The reossification of the epiphysis starts in the periphery after revascularization via the synovial membrane The fate of the metaphyseal defect is dependent on the severity of the cartilage lesion in the epiphyseal plate If the lesion is slight ossification commences at the margins of the metaphyseal defect If the lesion is severe the metaphyseal defect remains and is gradually filled out by the bony epiphysis The lesion in the epiphyseal plate is often of such a kind that contact is established between the vascular systems in the epiphysis and the metaphysis with local fusion of the epiphyseal line resulting

The greater trochanter Retardation of the longitudinal growth of the femoral neck and premature closure of the subcapital epiphyseal line are of frequent occurrence in coxa plana As a rule the growth of the greater trochanter is not affected It is thus obvious that a discrepancy between the femoral head and neck on the one hand and the greater trochanter on the other must result On the radiograms this is discernible as a reduction of the distance between the tip of the greater trochanter and the proximal pole of the femoral head in the present paper called the articulo-trochanteric distance ATD (Fig 26 p 95)

In the present study systematic measurements of the ATD were made It emerged that the reduction of the ATD which implies elevation of the greater trochanter occurred late in the reparative stage or after primary healing had taken place in those cases where the subcapital epiphyseal line fused prematurely In many cases the elevation of the greater trochanter was so marked that the tip of the trochanter reached several millimetres higher cranially than the upper pole of the head of the femur

The deformity in coxa plana The deformity caused by coxa plana has been discussed in the previous literature Some authors believe that the disease leads to a varus deformity while according to others it tends to cause a valgus deformity In these estimates the part of the greater trochanter in the modelling of the proximal end of the femur has been disregarded The greater trochanter is however an integrating part of the proximal end of the femur and cannot be ignored on assessing a possible varus or valgus deformity of the latter

An account is given of previous experimental and clinical observations on growth phenomena in the proximal end of the femur associated with distur

bances in the subcapital or subtrochanteric growth zones and a comparison is made with the conditions prevailing in the distal end of the femur The conclusion is drawn that in those relatively frequent cases of coxa plana in which the subcapital growth line is prematurely closed and the growth of the greater trochanter continues undisturbed throughout the normal growing period the ultimate deformity of the proximal end of the femur is a true varus deformity

Trendelenburg's sign In the present series a positive Trendelenburg sign was noted in 26 cases of ultimately healed unilateral coxa plana The ATD was reduced in all but one of these cases Among the 26 cases there were 9 in which a retrospective examination of the clinical data and the radiographs revealed that Trendelenburg's sign had been negative at a late reparative stage and that no or only a slight reduction of the ATD had been present The observations in the cases with positive Trendelenburg signs show that abductor insufficiency in coxa plana may develop at a very advanced stage of the disease as a result of elevation of the greater trochanter

Prevention of deformity by epiphysiodesis of the greater trochanter Since 1961 epiphysiodesis of the greater trochanter has been performed at the Orthopaedic Hospital of the Invalid Foundation in 25 cases of coxa plana in which radiological examinations revealed progressive reduction of the ATD or premature closure of the subcapital epiphyseal line In 23 cases which have been followed up the epiphysiodesis led to partial or complete fusion of the growth line of the trochanter and the reduction of the ATD was arrested by the operation These results seem to justify the conclusion that if epiphysiodesis of the greater trochanter is performed at a favourable point of time it appears to be possible to prevent elevation of the greater trochanter and consequent abductor insufficiency

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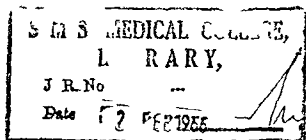
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Surgical Treatment of Spondylolisthesis without Spine Fusion

A Long Term Follow-up of Operated Cases

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Eight years ago in association with *Manning* the authors reported a group of eighteen patients treated for symptomatic spondylolisthesis by excision of the loose lamina and decompression of the nerve roots without spine fusion (5) The patho-mechanics of this condition the surgical technique the findings at surgery and the methods of post operative care were described at that time

The present paper is a long term follow up study of our operated cases in which we shall pay particular attention to the question of postoperative progression of displacement and our results

Our series now consists of fifty two patients between the ages of fourteen and fifty-seven years The two children in the group were fourteen years of age Forty three patients (twenty-one males and twenty two females) were treated initially by the decompression operation Two women had a combined decompression and fusion and seven women were treated by the decompression procedure after previous fusion operations had failed to relieve their symptoms Of the latter six had pseudarthroses but one had persistent symptoms despite a solid fusion

The present length of follow up on all of our patients extends from four to 146 months and averages sixty four months Twenty nine cases have been followed over sixty months Sixteen cases were lost after follow up periods of four to thirty seven months Ten of these have not been seen since our initial publication Therefore their radiographs have not been included in this article (Cases 1 6 8 9 10 11 12 17 19 and 20)

EVALUATION OF DISPLACEMENT

Most of our early x rays were obtained with the patients reclining All of the follow up x rays were taken in the upright position Comparisons between the reclining and upright films obtained on the same date show no essential change in the position of the involved vertebra

We used *Taillard*'s method (9 10) of expressing the displacement of the spondylolisthetic vertebra as a per cent of the width of the vertebra below This is illustrated in Table 3 The description of the degree of displacement follows *Meyerding*'s basic classification but is more detailed and is described in footnotes on Tables 1 E and 2 E

PROGRESSIVE FORWARD DISPLACEMENT IN THE CHILD

Friberg (3) reported that progressive forward displacement occurred over a relatively short period of time in a very few children in his series and in these cases spondyloptosis resulted

Taillard showed that progressive forward slipping occurred in twelve of the fifty cases in his series and only in patients under the age of twenty five years He believed that he could accurately predict rapid and complete forward displacement in those patients having both a decrease in the posterior vertical height of the fifth lumbar vertebra of 30 per cent or more in relation to the anterior height and a rounding of the superior border of the sacrum He reduced the deformity by Scherb's method obtained satisfactory repositions in seven of the thirteen cases attempted and performed postero-lateral fusions in these cases Of these seven cases six subsequently showed complete forward displacement He concluded that successful arthrodesis was ineffective in preventing progressive displacement

In our original paper we were aware that rapid forward displacement occurred in some children and we advised against the decompression procedure in children *Margo* (7) later reported the case of a young boy with considerable displacement whose symptoms were temporarily relieved by the decompression operation but who then showed additional displacement and developed more symptoms *Marmor & Bechtol* (8) reported an almost identical case In both of these cases fusions were performed after the slipping had progressed but unfortunately the lengths of follow up were brief

Taillard's criteria would have indicated the probability of progressive displacement in these two patients In our opinion removal of the arch contributed nothing to the increased displacement nor in most hands would initial fusion have prevented it

One of the two children in our series (Case 51) showed the typical changes mentioned by *Taillard* This boy had low back and leg pain and was treated with exercises until spondyloptosis occurred At sur

gery solid healing of the defect on the left and evidence of partial healing on the right were found In addition there was a spontaneous fusion of the inferior facet of the fifth lumbar vertebra to the sacrum on the left The decompression operation was performed and resulted in complete relief of symptoms He had some recurrence of difficulty fifteen months after surgery following an automobile accident but symptoms quickly subsided

The other child (Case 50) did not show the progressive displacement criteria of *Taillard* She was treated conservatively however for twenty eight months and no progression occurred At surgery no defect was demonstrable in either pars interarticularis or pedicle The lower end of the dural sac and the sacral nerve roots were compressed by a tight arch of the fifth lumbar vertebra A simple laminectomy was performed and the inferior facets were left intact She had relief of symptoms after surgery For nine months there was no further displacement but x rays twenty four months after surgery revealed a 22 per cent progression of displacement The patient was entirely asymptomatic however and the clinical examination was completely negative

In our experience most children become asymptomatic on a vigorous program of straight leg raising and toe touching exercises However if symptoms are persistent and severe we feel that the decompression operation may be done for relief of pain in most children since only one child out of ten is likely to show progressive displacement and since it now seems probable that we can predict which children will continue to slip

We believe there are two alternatives in those children who do have x ray findings indicative of continuing displacement If both arthrodesis and arrest of displacement could always be achieved then one would certainly be justified in doing a combined decompression and fusion operation particularly in females However if one could not be certain either of arresting displacement or of obtaining solid fusion as we cannot then one should inform the parents that further progression is likely and that surgery should be delayed until maximum displacement is reached We recommend deferring surgery because in some cases of severe displacement it is also necessary to excise the lamina above the spondylolisthetic vertebra to achieve a thorough decompression

PROGRESSIVE DISPLACEMENT IN THE ADULT

Twenty nine of our fifty adult patients have shown no postoperative progression of forward displacement after an average follow up of fifty nine months The remaining twenty one adults have shown varying amounts of progressive displacement during an average follow up period of eighty one months (See Tables 4 and 5) The average postoperative increase in displacement in all of our patients including the children is 5 per cent

Although this series of cases is too small to be of statistical value it is at least interesting to note that essentially the same percentage of men and women showed progression of displacement after surgery In the group showing progression the average increase was 5 9 per cent in males and 16 per cent in females Among the women Cases 2 5 16 18 25 29 and 50 showed the greatest progression and all but one were young Case 5 had two children before surgery and three afterward Case 16 had three children after surgery and Case 18 had one before the decompression and one afterward Cases 5 and 18 reported much easier pregnancies and deliveries after the decompression operation None of these women had any back difficulty during pregnancy or any complications with delivery

In the adults showing increase in slipping there were 90 per cent satisfactory results and 10 per cent failures whereas there were 82 7 per cent satisfactory cases and 17 3 per cent failures in the group who showed no progression These figures substantiate our opinion that there is no correlation between symptoms and the degree or progression of displacement in adults with spondylolisthesis

Case 5 a woman who has been followed for 123 months is of particular interest to us because she has shown considerable progression of displacement (27 per cent) and because we obtained follow up x rays on her at close enough intervals to learn when the progression occurred Tracings of the x rays appear in Table 3 Progression was first noted thirty eight months after surgery and was associated with narrowing of the lumbosacral disc The progression and narrowing continued over the next forty three months until the disc collapsed completely Displacement has not progressed in the past three years but seemingly has regressed 6 per cent During the period of increasing displacement this patient had no symptoms After the disc collapsed and displacement stopped she began to have episodes of back and leg discomfort after lying in bed for several hours She could obtain relief

by getting up and exercising This patient certainly did not fit the typical clinical picture of so-called instability since the erect position and activity relieved the symptoms which she had

Aside from Case 5 x rays were not taken at the proper intervals to show precisely when progression of displacement occurred in the other adults It would appear however from the patients whom we have followed for a long period of time (Cases 2 4 5 13 15 16 28 and 29) that progression of displacement after the decompression operation is generally mild occurs in association with narrowing and degeneration of the lumbosacral disc and in itself does not cause symptoms

Adkins (1 2) described two patients who showed some increase in forward displacement after excision of the arch In each case he removed the posterior annulus of the disc in order to perform an inter body fusion which then could not be done because of deterioration in the patient s condition during surgery He felt that removal of the posterior annulus might have been the cause of the additional displacement which later occurred

The preservation of the posterior annulus may therefore be important to the maintenance of stability in this condition Also the build up of bone along the anterior superior portion of the sacrum which is frequently seen in patients with spondylolisthesis may well be due to the stripping away of the annulus from this portion of the sacrum

SPONTANEOUS HEALING OF THE DEFECT

Several cases listed on Table 1 C had a build up of bone about the defects in the pars interarticularis which seemed to indicate attempted healing and in four patients we found evidence of complete healing

In Case 24 the defect on the right showed healing by bone In Case 42 although the appearance by x ray was characteristic of a typical first degree spondylolisthesis at surgery both defects were found to be completely filled in with bone Symptoms in this case were obviously caused by the massive bone formation which compressed the fifth lumbar roots at the sites of the healed defects This patient also had a spontaneous fusion of the inferior facet of the fifth lumbar vertebra to the superior facet of the sacrum on the left

Case 50 had the typical appearance of spondylolisthesis but at surgery no defects were found in the arch and the symptoms appeared to be due to compression of the sacral nerve roots and the dural sac by the tight arch

Despite the rapid occurrence of spondyloptosis before surgery in Case 51 the defects in the fifth lumbar vertebra were found to be healed completely on the left and partially on the right This patient also had a spontaneous unilateral fusion of the inferior facet of the fifth lumbar vertebra to the sacrum on the left

A spontaneous and very solid fusion of both inferior facets of the fifth lumbar vertebra to the sacrum was also found in an adult with spondyloptosis (Case 28)

DEVELOPMENT OF PSEUDARTHROSIS FOLLOWING SOLID FUSION

We have found that patients with spondylolisthesis may develop pseudarthrosis even many years after apparent solid fusion is present

Case 3 was treated initially in 1949 by a *Hibbs* fusion from the fourth lumbar vertebra to the sacrum without decompression Fourteen months later because of persistent left leg pain a re exploration was carried out for removal of the fibrocartilaginous mass which was felt by that time to be the cause of her symptoms The fusion was found to be heavy and solid A hole was drilled through the one inch thick fusion mass on the left side at the fourth lumbar interspace to gain exposure of the defect Seventy four months following the initial fusion a pseudarthrosis developed at the lumbosacral interspace Interestingly enough however the fusion remains solid at the fourth lumbar level

Another patient (Case 27) had two unsuccessful fusions in 1939 and 1940 A third fusion in 1942 was reported to be solid from the third lumbar vertebra to the sacrum She continued to have constant pain for several years and then intermittent symptoms for an additional period of time until we saw her in 1955 At surgery pseudarthroses were present at the third and fifth lumbar interspaces

An interesting study would be a long term follow up and search for pseudarthrosis in the apparently successful fusions for spondylolisthesis by those medical centers where arthrodesis has long been the standard treatment for this condition By this study also more information could be gained about the secondary development of defects in the pars interarticularis of the vertebra above the fusion area Incidentally we have never seen such a defect occur following excision of the loose arch alone

ASSOCIATED DISC PATHOLOGY

Most patients with spondylolisthesis have degeneration of the fifth lumbar disc and usually the nuclear material is displaced anteriorly rather than posteriorly

In our fifty two cases one third of the patients had disc pathology which may have accounted for the onset of symptoms We found four herniations and ten protrusions of the fourth lumbar disc and at the fifth lumbar level we found one herniation and three protrusions In some of these cases the disc pathology rather than the spondylolisthesis appeared to be the sole cause of symptoms

Therefore the prevalent concept that onset of symptoms following injury in patients with spondylolisthesis merely represents an aggravation of a pre existing condition is no longer valid and in these cases serious consideration should always be given to the coexistence of disc pathology

REOPERATION FOLLOWING THE DECOMPRESSION PROCEDURE

a Unsuspected or Recurrent Disc Pathology

A herniation of the fourth lumbar disc was found in Case 40 at the time of the initial decompression Symptoms persisted and upon re exploration three months later a herniated disc was also found at the third lumbar interspace

In Case 42 discography two years postoperatively showed a new protrusion of the fourth lumbar disc and a protrusion of the third lumbar disc Symptoms however have not been sufficient to warrant re exploration and the patient continues to perform extremely heavy work

In those patients with involvement of the patellar reflex discography at the third lumbar interspace should be done prior to surgery

Case 36 was found to have a herniation of the fourth lumbar disc at the time of initial surgery He had a perfect result until he was involved in an automobile accident thirty four months postoperatively and again developed symptoms Re exploration revealed a reherniation of the fourth lumbar disc

Case 37 developed recurrence of symptoms one month after surgery as a result of a fall Seventeen months later a herniated disc was found and excised A reherniation at the same level occurred after numerous subsequent injuries and was removed thirty one months after the

initial surgery This patient often exhibits classical symptoms of conversion hysteria Although she is classified as a failure there are times when she gets along quite well

b Meningocele

Recurrence of local symptoms in the back and coccygeal area necessitated re exploration in two other patients in whom meningoceles were found

In Case 11 re exploration was performed nineteen months after the decompression operation and resulted in considerable relief of symptoms

In Case 49 the original decompression had been done elsewhere and had completely relieved symptoms for over five years Local back pain recurred however and upon re exploration seventy one months after the original surgery a very large meningocele was found and excised The patient developed a postoperative staphylococcal infection which resulted in a spinal fluid fistula This closed spontaneously after a period of bed rest in the head dependent position He returned to work four months after surgery and has been doing heavy welding work for the past three years without symptoms

It is probable that these meningoceles resulted from needle holes in the dura following myelography or discography At the time of surgery small dural defects should be sought and carefully closed with fine arterial silk

c Extraneural Scarring

Extraneural scarring may occur after surgery for spondylolisthesis as well as after any lumbar disc excision

Case 5 described previously developed left first sacral root findings *nine and one half years after the original decompression* Upon re exploration the first sacral root was found to be tented and bound down by scar and the root was released While being driven home from the hospital the patient was involved in an automobile accident she was thrown out on the road and the wound was torn open The wound healed nicely again but the patient has shown little if any improvement However there may understandably be a large element of psychic trauma as a result of this accident

Case 44 was re explored for scarring about the fifth lumbar root and

obtained some relief but this patient s symptoms are difficult to evaluate because of a coexistent severe plantar fasciitis

Extraneural scarring may occur for several reasons Re exploration of patients after disc surgery has shown that incomplete excision of the ligamentum flavum results in its becoming bound down to the dura and emergent nerve roots For this reason there should be complete excision of ligamentum flavum from areas adjacent to the nerve roots

A second cause for scar formation results from the use of cottonoid as a packing and sponging material Reports of microscopic sections of extraneural scar frequently stated that suture material was present in the scar Since none had been used in the area it was obvious that the excessive scar was due to irritation from minute pieces of cottonoid For the last several years we have substituted polyvinyl sponge (*Ivalon*) in our cases This material is more resilient tougher than cottonoid and suction through it is superior to cottonoid

A third reason for extraneural scar we believe lies in the individual Patients with dark complexions tend to form excessive scar about the dural sac and emergent nerve roots This deep scar is almost always associated with visible keloid in the skin wound Patients with dark complexions have therefore been given deep x ray therapy beginning on the third postoperative day

d Intraneural Scar

Intraneural scar can exist prior to surgery as a result of prolonged root irritation and compression at the defect It can also be caused by undue trauma at the time of surgery These patients may have persistence of back and leg symptoms despite the presence of free straight leg raising It is our practice therefore to divide the sheath carefully if the root appears scarred at the time of surgery Neurolysis seems to give relief in about half of the cases attempted We find it impossible to predict however which patients may continue to have symptoms caused by intraneural scar formation

e Fusion after Arch Excision

Of the forty three patients treated initially by decompression we have subjected only two to attempted fusions later because of the persistence of symptoms following the decompression operation Interbody fusion was performed elsewhere in a third patient

The first patient (Case 21) had an attempted decompression operation elsewhere When we explored him eleven months later we found that the lateral portions of the arch and the cartilaginous mass had not been removed on either side and there was considerable scar formation about the roots Radicular pain continued after our decompression so five months later following discography which showed a protrusion of the fourth lumbar disc and marked degeneration of the fifth disc evacuation of these two disc spaces was attempted This procedure did not relieve symptoms either Therefore an *Adkins* fusion was attempted and resulted in fusion of the fourth to the fifth lumbar vertebrae but not of the fifth lumbar vertebra to the sacrum even though very little motion remained at this level The patient was improved by this procedure and was able to obtain a job as a swimming pool maintenance man Five years later he suddenly complained of an increase in sciatic pain and also had an episode of delirium tremens We refused to subject this man to further surgery but a month later another fusion operation was attempted elsewhere This too failed to relieve his symptoms We do not know whether solid fusion was obtained on the last occasion

The second patient (Case 41) had severe right sciatica and marked right fifth lumbar root findings At the initial surgery the fifth lumbar root was found to be impaled upon a spur arising from the right lateral portion of the loose lamina of the involved vertebra Relief of pain *followed the decompression However there was recurrence of severe* right leg pain and some back pain and nine months later an *Adkins* fusion was attempted The right leg pain was not relieved so after another nine month interval the sensory component of the right fifth lumbar root was divided under local anesthesia Symptoms were diminished for two years but the patient again returned because of low back and right leg pain The fusion was then reinforced over the facet area At surgery we found no motion between the fifth lumbar vertebra and the sacrum but some was evident between the fourth and fifth lumbar vertebrae This procedure did not relieve symptoms or result in fusion of the fourth to the fifth lumbar vertebrae One and one half years later we again explored the patient but were still unsuccessful in relieving her symptoms This woman is overweight and has been having severe personal difficulties and these factors may play some part in the persistence of her symptoms

Case 31 a cerebro spastic palsy victim with spastic paralysis of the lower extremities and a marked lumbar lordosis had the decompres

sion operation performed for low back and left sciatic pain Although she was improved moderately by the surgery the leg pain continued Four years later at a local clinic an anterior interbody fusion at the fourth and fifth lumbar levels was unsuccessful Three months later a re exploration also failed to relieve her symptoms After these two operations the patient was confined to a wheel chair We re explored the site of the decompression a year later Considerable scar was re sected and the patient was placed on an active postoperative course of exercises and swimming She returned to college was ambulatory without crutches and was able to carry out the activities which she had been incapable of performing following the attempted fusion

Our experience with the fusion operation for various types of low back conditions indicates that it will not relieve radicular pain

OTHER COMPLICATIONS OF SURGERY

a Wound Infections

Wound infections occurred in two patients (Cases 40 and 49) but fortunately did not adversely affect the final results

b Thrombophlebitis and Pulmonary Embolism

One case of thrombophlebitis occurred in this series (Case 3) This patient had a conventional fusion operation in 1949 and developed a thrombophlebitis during the postoperative period She continues to have some swelling of the involved leg

Case 1 who initially had a combined decompression and fusion operation developed a mild pulmonary embolism after a secondary decompression operation was done for removal of bony fragments which had sunk in on the dural sac

In general however our entire series of cases seems to be singularly free from the complications of thrombophlebitis or pulmonary em bolism and we believe this is because of the early exercise and ambu lation permitted by the decompression procedure

c Poor Patient Selection

Poor patient selection is another cause of poor results after any operative procedure In this series we have four patients who show definite evidence of conversion hysteria (Cases 30 33 37 and 41) Two other patients were extremely neurotic and one we learned later was

a chronic alcoholic If any overt emotional problems are apparent in a patient we do not believe that he is a candidate for any type of back surgery

We also feel that this procedure should be used with caution in patients who have litigation pending For example Case 33 who was noted above to have a conversion hysteria had an industrial injury and claimed no improvement after surgery although there were no positive findings at the time we last saw him Three other patients however were involved in accidents and subsequent litigation and all showed prompt relief of symptoms following surgical treatment (Cases 11 16 and 36)

RESULTS

Our cases were analyzed according to *Barr's* criteria except that those cases which required reoperation were not automatically considered failures This change was necessary in all fairness because many of our patients sustained injuries after surgery and because excellent results by the fusion method are reported in many papers but two or more operations were often necessary to achieve the reported results

a Initial Decompression

Of the forty three cases of initial decompression 86 1 per cent are considered satisfactory and 13 9 per cent unsatisfactory Eighteen or 41 8 per cent are asymptomatic twelve or 28 per cent are good seven or 16 3 per cent are fair and six or 13 9 per cent are failures If one considers only the twenty four cases in this group who have been followed over five years the results are very little different twelve or 50 per cent are asymptomatic four or 16 7 per cent are good three or 12 5 per cent are fair and five or 20 8 per cent are failures

b Combined Arch Excision and Fusion

In our group there were only two patients who had combined arch excision and fusion as one operative procedure The first (Case 1) did well for a period of time but then developed a pseudarthrosis and recurrence of symptoms She was markedly improved following a second decompression procedure but was finally lost from further follow up She was considered to have a fair result

The second patient (Case 2) developed recurrence of back and leg pain soon after the initial surgery Re exploration showed that the grafts had slipped medially causing irritation and pressure on the lower dural sac and necessitating removal of the bony material Re fusion with rib grafts was attempted but although solid fusion was obtained it did not result in complete relief of symptoms However the patient does quite well at this time and is considered to have a fair result

c Decompression after Previously Attempted Fusion

The six remaining patients in this series were treated by the decompression operation after attempted fusion had failed to relieve their symptoms One is considered to have a good result four patients are classified as fair and one is a failure

Case 18 had three unsuccessful fusions and was finally advised to seek psychiatric care before we first saw her While under our care she has had four additional operations the last over three years ago when a new protrusion of the fifth lumbar disc was removed She has a fair result but feels much better and now is able to participate in sports such as water skiing and bowling She also holds a full time job in addition to doing her housework and caring for her two children

Case 27 had three fusion operations was able to work for fifteen years and then became completely disabled Following the decompression she has been able again to do her regular work and is listed as a fair result

Case 30 shows evidence of a classical conversion hysteria but actually has a fair result following the decompression operation

Case 9 a good result and Case 25 a fair result were improved after the decompression but have been lost from further follow up Case 17 was classified as a failure on the basis of her complaints although all physical neurological and x ray examinations were normal

Although our results in this group of cases are not striking they do illustrate that patients who are completely disabled following attempted fusion operations can be rehabilitated by the decompression procedure

CONCLUSIONS

Our experiences gained from treating symptomatic spondylolisthesis by the techniques which we have developed over the past thirteen years are briefly summarized as follows

1 These patients should first be treated with an active exercise pro

gram consisting of straight leg raising and sitting toe touching exercises The use of a brace or any type of support has usually only aggravated symptoms

2 Surgery is considered necessary in those patients who despite the treatment outlined above continue to have severe symptoms or in those who are prevented from enjoying normal lives because of recurrent episodes of disability

3 From our limited experience it appears that the decompression operation may also be used in children whose symptoms are persistent and severe In those who show the progressive displacement criteria of *Taillard* treatment should only be undertaken after a thorough discussion with the parents regarding the probability of further forward displacement

4 Anterior displacement of varying degrees occurs in a few adults after the decompression operation This begins as a narrowing of the disc below the involved vertebra is limited and does not necessarily lead to onset of symptoms The same percentage of men and women showed postoperative progression of displacement but a greater degree of displacement occurred in women Most of the women were within the child bearing age and three had from one to three children following the decompression operation In our opinion removal of the arch neither causes further forward displacement nor influences its amount

5 Aside from the usual degenerative changes at the fifth lumbar disc disc protrusion or herniation at other levels is present in one third of the cases It most commonly occurs at the interspace above the spondylolisthetic vertebra where the greatest stress is placed because of the small amount of motion present between the involved vertebra and the one below

6 Results of the decompression operation we feel are satisfactory under the following conditions

a The procedure must be performed thoroughly by complete removal of the arch and decompression of the involved roots past the pedicles

b Disc pathology should be recognized and dealt with at the time of surgery

c The postoperative care must consist of the prompt initiation of straight leg raising exercises and later toe touching exercises in order to insure free nerve root excursion Complications such as thrombophlebitis and pulmonary emboli will also thus be avoided

7 If patients develop recurrence of symptoms following surgery one should not hesitate to reoperate after employing the usual diagnostic methods of thorough neurological examination plus myelography and/or discography

8 In our experience attempts at fusion after arch excision because of persistent radicular symptoms will not relieve pain arising from nerve root involvement In addition fusion is difficult to achieve

TABLE

Synopsis of Cases of Spondylolisthesis Originally Treated

Case	Sex	Age	Occupation	Onset with injury	Duration of symptoms	Length of conservative treatment
4	M	41	Physician	No	5 years	5 years
5	F	30	Housewife	No	5 years	4 years
6	M	37	Salesman	No	2 years	18 months
7	F	23	Housewife and secretary	No	2 weeks	None
8	M	37	Laundryman	No	9 years	9 years
10	F	44	Housewife	No	14 years	10 years
11	F	27	Secretary	Yes	16 months	16 months
12	F	27	Housewife	No	4 years	1 year
13	M	35	Floor covering contractor	Yes	Many years worse last 15 months	4 months
14	M	19	Clerk and laborer	Yes	4 months	1 month
15	F	24	Housewife	No	2 years	18 months
16	F	25	Clerk and housewife	Yes	7 months	7 months
19	M	23	Medical student	No	Several years	10 months
20	M	40	Teamster	No	2 years	1 year
21	M	32	Carpenter	No	2 years	2 years
22	M	52	Marine electrician	No	All of life worse last 7 years	7 years
23	F	41	Clerk	Yes	9 months	9 months
24	M	51	Janitor	Yes	24 months	24 months
26	F	47	Bookkeeper	Yes	Many years worse last 2 months	2 months

1—A
by Excision of the Loose Arch and Decompression Alone

L lan l d gr of l spl c n nt	A t lan m l	D gr of p op t e d sabil t
Lumbar 5 first	Upper lumbar curve left	Total
Lumbar 5 first	Mild thoraco lumbar curve left	Total
Lumbar 5 first	Bifid lamina lumbar 5 with fusion to spinous process of sacral 1 Spina bifida occulta of sacral 1	Total
Lumbar 5 first	Upper lumbar curve right	Total
Lumbar 5 first	Spina bifida occulta sacral 1	Total
Lumbar 5 first	None	Moderate
Lumbar 5 first	Thoraco lumbar scoliosis left	Total
Lumbar 5 first	Bifid lamina lumbar 5 Spina bifida occulta sacral 1	Total
Lumbar 5 first	Spina bifida occulta sacral 1 with fusion spinous processes lumbar 5 and sacral 1	Total
Lumbar 5 first	None	Moderate
Lumbar 5 second	None	Total
Lumbar 5 first	Mild upper lumbar curve left	Total
Lumbar 5 first	Spina bifida occulta sacral 1	Total
Lumbar 5 first	Lumbar curve right	Moderate
Lumbar 5 first	Upper lumbar curve left	Total
Lumbar 4 first	Reverse" spondylolisthesis lumbar 5	Total
Lumbar 5 spondylolysis	Unilateral defect lumbar 5 left Bifid lamina lumbar 5	Total
Lumbar 5 first	Spina bifida occulta sacral 1 with fusion spinous processes lumbar 5 and sacral 1 Healing of defect lumbar 5 right found at surgery	Total
Lumbar 5 first	Mild right thoraco lumbar curve	Total

TABLE

Case	Sex	Age	Occupation	Onset with injury	Duration of symptoms	Length of conservative treatment
28	F	38	Bookkeeper and housewife	No	16 years	11 years
29	F	47	Shipping clerk and housewife	No	4 5 years	4 years
31	F	21	Student	Yes	5 years	11 months
32	M	51	Janitor	No	10 months	10 months
33	M	49	Painter	Yes	1 year	1 year
34	M	37	Grocery clerk	Yes	1 month	1 month
35	M	36	Teacher	No	2 5 years	5 months
36	M	38	Truck driver	Yes	1 year	8 months
37	F	40	Waitress and housewife	No	3 years	1 year
38	F	38	Waitress	Yes	20 years	Several years
39	M	45	Banker	Yes	Several years	8 months
40	F	36	Housewife and magazine sales	Yes	1 year	4 months
41	F	30	Maid and housewife	Yes	3 years	3 years
42	M	47	Construction worker	No	5 years	4 5 years
43	F	57	Assembly worker	No	9 weeks	5 weeks
44	F	55	Housewife	No	14 years	13 years
45	F	57	Housewife	No	5 years	4 years

—4 (cont)

Le el and degree of li plac ment	A t l a iom l	D ree of pr operati e d s bilit
ımbar 5 fourth	Fusion of facets lumbar 5 to sacrum found at surgery	Total
ımbar 5 first	Spina bifida occulta sacral 1	Moderate
ımbar 5 first	Cerebro-spastic palsy	Questionable because of palsy
umbar 5 first	None	Total
umbar 5 spondylolysis	None	Qu stionable
umbar 5 first	Mild thoraco lumbar curve left Fusion spinous processes lumbar 5 and sacral 1	Total
umbar 5 first	Bifid lamina lumbar 5	Total
umbar 5 first	Mild mid lumbar curve left Bifid lamina lumbar 5 Spina bifida occulta sacral 1	Total
umbar 5 first	Porphyrinuria diagnosed after surgery	Total
umbar 5 first	Right lumbar left thoracic scoliosis	Total
umbar 5 first	Mild left lumbar curve Bifid lamina lumbar 5 Spina bifida occulta sacral 1	Total
umbar 5 first	Left thoraco lumbar scoliosis Sustained compression fractures of thoracic 9 and lumbar 1 65 months after initial surgery	Total
umbar 5 first	Slight left upper lumbar curve Spike of bone down from right lamina of lumbar 5 to nerve root found at surgery	Total
umbar 5 first	Right thoraco lumbar scoliosis Fusion inferior facet lumbar 5 to superior facet sacral 1 left and bilateral healing of defect lumbar 5 found at surgery	Total
umbar 5 first	Right lower thoracic curve	Total
umbar 5 first	Right mid thoracic curve Chronic plantar fascitis Negative for rheumatoid arthritis	Moderate
Lumbar 5 first	Right mid thoracic left low thoracic curve mild	Total

TABLE

Case	Sex	Age	Occupation	Onset with injury	Duration of symptoms	Length of conservative treatment
46	F	29	Brushmaker and housewife	No	7 years worse last 10 months	10 months
47	M	57	Automobile painter	Yes	6 5 years	6 years
48	F	46	Housewife	Yes	8 years worse last 1 year	8 years
49	M	48	Welder	No	10 months	9 months
50	F	14	Student	Yes	4 years	28 months
51	M	14	Student	No	27 months	26 months
52	M	52	Farmer	Yes	Many years worse last 6 weeks	6 weeks

Total = Unable to carry out any activities Severe back and (or) lower extremity pain
Moderate = Unable to carry out most activities Moderate back and (or) lower extremity pain
Mild = Able to carry out most activities Mild pain in back or lower extremities

1—A (cont.)

Level and degree of displacement	Associated anomalies	Degree of preoperative disability
Lumbar 5 first	None	Total
Lumbar 5 first	Spina bifida occulta sacral 1 Fusion spinous processes lumbar 5 and sacral 1	Total
Lumbar 5 first	None	Total
Lumbar 4 first	Mild left mid lumbar curve	Total
Lumbar 5 first	Left lumbar curve Spina bifida occulta sacral 1	Total
Lumbar 5 fourth	Osteochondritis Mild left lumbar curve Progression of forward displacement from second to nominal fourth degree allowed to occur before surgery	Total
Lumbar 4 first	Right upper lumbar curve Transitional fifth lumbar vertebra	Total

TABLE

Comparison of Symptoms and

		Preoperative		
Case	Back pain	Area of radicular pain	Abnormal physical findings	Nerve roots involved
4	Moderate	Left sciatica severe	Flexion 18 in of floor SLR 80 right 3 left	Lumbar 5 sacral 1 left moderate
5	Moderate	Calves severe	Extension restricted and painful	Lumbar 5 left moderate
6	Mild	Buttocks Left sciatica severe	Flexion 6 in of floor Extension restricted and painful SLR 80 right 60 left	Lumbar 5 sacral 1 left moderate
7	Moderate	Buttocks severe	Flexion 4 in of floor Extension restricted and painful	Lumbar 5 right moderate
8	Severe	Right buttock severe	Flexion 18 in of floor Right list Extension restricted and painful SLR 10 right 60 left	Lumbar 5 sacral 1 right moderate
10	Moderate	Coccyx and right sciatica moderate	Extension restricted and painful SLR 60 right 90 left	Lumbar 5 sacral 1 right moderate
11	Mild	Left sciatica severe	Flexion 10 in of floor Extension restricted and painful	Lumbar 5 sacral 1 left moderate
12	Severe	Left sciatica severe	Extension restricted and caused increase in radicular pain and neurological findings	Lumbar 5 left moderate
13	Severe	Right buttock and sciatica moderate	Extension restricted and caused increase in radicular pain and neurological findings	Right lumbar 5 moderate sacral 1 mild
14	Moderate	Sciatica moderate Right buttock	Extension restricted and caused increase in radicular pain and neurological findings	Lumbar 5 bilateral moderate Sacral 1 right mild
15	Severe	Posterior thighs severe	Flexion 18 in of floor SLR 80 right 70 left Extension restricted and painful	Lumbar 5 bilateral severe Sacral 1 right moderate

1—B
Findings before and after Surgery

	Postoperative (most recent examination)		
Backpain	Amount of radicular pain	Abnormal physical findings and remarks	Nerve roots involved
Occasional ache	Occasional left sciatica	Carries out full practice including long periods in surgery daily	Lumbar 5 sacral 1 mild
Occasional ache	Occasional left sciatica	Touches floor 2 pregnancies postoperatively Reoperated See Table 1—D	Sacral 1 left
None	Occasional right calf mild	Flexion to 4 in of floor Examination negative	None
None	None	3 pregnancies postoperatively Examination negative	None
None	None	Flexion to 3 in of floor Examination negative	None
Occasional mild	None	Flexion 2 in of floor Examination negative	None
None	Right thigh and buttock, moderate	*Flexion 12 in of floor SLR 60* right 75 left Reoperated See Table 1—D	None
None	None	Touches floor Examination negative	None
None	None	Acute flare up 8 5 years after surgery Findings indicated possible disc protrusion Subsided in 1 week Again asymptomatic and examination negative	None
None	None	Examination negative except for recent right peroneal palsy caused by habit of sitting with right leg crossed over left during prolonged periods of studying	None other than right peroneal palsy
Occasional catching	Occasional left calf ache	Touches floor	Lumbar 5 left mild

TABLE

Preoperative				
Case	Back pain	Area of radicular pain	Abnormal physical findings	Nerve roots involved
16	Moderate	Lateral right calf severe	Extension restricted and painful	Lumbar 5 right moderate
19	Mild	Sciatica right severe	Flexion 2 in of floor SLR 60 right 80 left	Sacral 1 right moderate
20	Moderate	Left buttock moderate	None	Lumbar 4 and 5 left mild
21	Severe	Sciatica bilateral moderate	Extension restricted and painful and caused increase in radicular pain and neurological findings	Lumbar 5 bilateral sacral 1 right moderate
22	Severe	Severe right sciatica	Moderate spasm Flexion 15 in of floor SLR 60 right 70 left	Lumbar 4 and 5 bilateral moderate
23	Mild	Severe right sciatica	Extension restricted and painful Slight spasm SLR 60 right	Lumbar 5 sacral 1 bilateral moderate left severe right
24	Only on hyper extension severe	Left sciatica severe	Flexion 7 in of floor SLR free but painful Extension reproduced left sciatic pain	Lumbar 5 bilateral worse on left Left sacral 1 severe
26	Severe	Inner thighs moderate	Two stage recovery from flexed position Spasm	Lumbar 5 right moderate
28	Severe	Posterior thighs and calves severe	Flexion 6 in of floor SLR free Extension painful Unexplained urinary incontinence	Lumbar 5 sacral 1 bilateral severe
29	Moderate	Bilateral sciatica moderate	Flexion free Pain on extension	Lumbar 5 right moderate Sacral 1 left mild

1—B (cont)

Postoperative (most recent examination)			
Back pain	Area of radicular pain	Abnormal physical findings and remarks	Nerve roots involved
None	None	Touches metacarpal heads to floor Examination negative 3 pregnancies postoperatively	None
None	None	Flexion 4 in of floor SLR 80 bilaterally	None
None	None	Touches floor Examination negative	None
Occasional severe	Occasional left great toe severe	No abnormal clinical findings Neurologic examination shows objective left sacral 1 findings but only subjective left lumbar 5 findings Reoperated See Table 1—D	Sacral 1 left
None	None	Flexion 6 in of floor Examination negative	None
Stiffness	Cramping in calves worse on right	Flexion 1 in of floor SLR 90 bilaterally	Bilateral lumbar 5 sacral 1 mild
Rare catch of pain	None	Touches floor Extension slightly restricted	None
Moderate	None	Examination negative Touches floor	None
None	None	Urinary incontinence disappeared	Bilateral lumbar 5 mild
None	Very mild buttock pain on right	Flexion to hands flat on floor Examination negative	None

TABLE

			Preoperative	
Case	Back pain	Area of radicular pain	Abnormal physical findings	Nerve roots involved
31	Severe	Sciatica left severe	Flexion only to knees due to spasticity Neurological evaluation difficult because considerable paralysis	Lumbar 5 left suggestive
32	Severe	Coccyx severe both legs to heels worse on left	Flexion 16 in of floor Little lumbar motion SLR 70 right with leg pain and 50 left with back pain	Sacral 1 left
33	Constant dull ache	Constant in right lateral thigh	Industrial injury Slight left list Flexion 2 in of floor No spasm or two stage recovery Compromise and release recommended initially on basis of definite exaggeration of complaints	Lumbar 5 right mild
34	Severe	Right sciatica moderate	Right list Back motions restricted and painful SLR 60 right positive Lasegue SLR 80 left	Lumbar 5 bilateral moderate worse on right
35	Moderate	Left calf severe Right leg intermittent	Flexion to 8 in of floor SLR 70 bilaterally	Lumbar 5 left moderate
36	Left moderate	Left sciatica severe	Left list Deviation to left on flexion SLR 80 right with pain left back SLR 45 left	Lumbar 4 sacral 1 left mild
37	Severe	Right sciatica severe	Flexion mid way between knees and ankles SLR 45 right 90 left	Lumbar 5 sacral 1 right moderate
38	Severe	Right thigh	Extension restricted and painful SLR tight bilaterally and painful on right	Sacral 1 right mild
39	Severe	Both buttocks Both legs	Rigid back Flexion to knees Right list SLR 80 right Tender over loose arch	Lumbar 5 right moderate

1—B (cont)

Postoperative (most recent examination)			
Back pain	Area of radicular pain	Abnormal physical findings and remarks	Nerve roots involved
Moderate	Left leg moderate	SLR free Touches toes No two stage recovery from flexion Reoperated See Table 1—D	Difficult to evaluate
None	None	Flexion to 3 in of floor Examination negative	None
Morning stiffness	Left sciatica	Camptocormia Stocking hypesthesia entire right lower extremity and left leg below knee Normal back motion SLR past 90 bilaterally Only positive finding was right heel jerk depression	Sacral 1 right mild
Tired feeling with over activity only	Some tenderness dorsum of right foot	Touches floor Slight left list which increases with fatigue but is not associated with any pain SLR 85 right 90 left	Lumbar 5 right mild
None	None	Touches floor Examination negative	None
None	None	Touches floor Had re injury after surgery See Table 1—D Completely asymptomatic and doing everything	None
Constant Varies in degree and location	Both legs intermittent worse on right	SLR slightly restricted and causes back and leg pain Flexion good from sitting position Atrophy of 0 25 in right calf 1 in left thigh	Lumbar 4 right and lumbar 5 bilateral mild
None	None	Flexion to palms flat on floor Examination negative	None
None	None	Clinical examination negative Only neurologic finding is slight depression both heel jerks	Sacral 1 bilateral slight

		Preoperative		
Case	Back pain	Area of radicular pain	Abnormal physical findings	Nerve roots involved
40	Severe	Coccyx left buttock entire right leg severe	Left list Flexion and right bend restricted and painful SLR 70 right with pain SLR 90 left with tightness	Lumbar 5 right moderate
41	Severe	Severe right sciatica into all toes	Rigid back Unable to straighten up SLR 15 right 45 left Loss of dorsiflexor power right foot	Lumbar 5 right severe
42	Severe	Both hips and legs worse on right	Flexion restricted and painful SLR 70 right 80 left	Lumbar 5 bilateral moderate worse on right
43	Severe	Right hip thigh and ankle moderate	Acute tenderness right sciatic notch Flexion caused right leg pain SLR 80 right	Lumbar 5 right severe
44	Moderate	Right thigh moderate	Flexion to 4 in of floor SLR 70 bilaterally	Lumbar 5 right moderate
45	Moderate	Left sciatica into great toe severe	Good back motions SLR free	Lumbar 5 left moderate
46	Moderate	Left leg severe Right leg mild	Flexion to 6 in of floor SLR tight Tender over loose arch	Lumbar 5 sacral 1 right moderate
47	Severe	Left calf severe	Back motions restricted SLR 70 left	Lumbar 5 sacral 1 left

1—B (cont)

Postoperative state (most recent examination)			
Back pain	Area of radicular pain	Abnormal physical findings and remarks	Nerve roots involved
None	Right calf mild	No low back discomfort Some pain over fracture site above Touches floor Numerous re injuries Reoperation See Table 1 —D	None
Intermittent ache varying intensity	Persistent severe right sciatica	Prompt return lumbar 5 right nerve function Flexion 12 in of floor Severe home problems Nail biter Reoperated See Table 1 —D	None
Mild Occasional	Right leg mild	Flexion to 3 in of floor Some discomfort on extension Works 15 hrs per day on maintenance heavy highway equipment Back discomfort on lifting more than 150 pounds	Lumbar 5 sacral 1 left mild
None	None	Slight tenderness right sciatic notch Abdominal discomfort SLR free Symptoms probably due to coexistent arteriosclerotic vascular disease	None
Constant Moderate	Right calf mild	Touches floor but complains of pain on bending Acute plantar fascitis Reoperated See Table 1—D	Sacral 1 bilateral mild
None	Right buttock occasionally	Asymptomatic until a fall 2 years after surgery Now has some pain on hyperextension Right buttock pain only after prolonged inactivity	None
Mild ache	None	Flexion to 6 in of floor Had re injury	None
Stiffness onl	Both legs mild	Only symptom was slight back stiffness after long inactivity until injured in auto accident 15 months after surgery Recent x ray evidence of increased spurring at lumbar 3 disc	None

TABLE

Preoperative				
Cas	Back pain	Area of radicular pain	Abnormal physical findings	Nerve roots involved
48	Aching severe	Both thighs intermittent severe	Good back motions SLR 70 bilaterally with pain Tender over loose arch	Lumbar 5 bilateral mild Sacral 1 left moderate
49	*Severe*	*Left buttock* and posterior thigh both calves	*Initial decompression elsewhere* Previous examiner reported spasm restriction all back motions and SLR 50 bilaterally See Table 1—D	*None* reported
50	Severe	Both legs to heels worse on right	Extension painful SLR 50 right 85 left	Lumbar 5 sacral 1 right
51	Severe only present on jarring motions	Both legs worse on left present only after prolonged walking	Marked lordosis Flexion restricted and caused leg pain bilaterally Unable to walk on toes of left foot	Lumbar 5 bilateral worse on left Sacral 1 left mild
52	Severe	Both legs severe	Marked left list Marked restriction SLR with pain Rigid back	Lumbar 4 sacral 1 bilateral lumbar 5 left

SLR = Straight leg raising

1-B (cont)

Postoperative (most recent e amin tion)			
Ba k p in	Ar a of rad cul r pa n	Abnormal pl ysi al findi g nd r ma k	Nerv oots invol d
None	None	Completely negative in all respects	None
None	None	Flexion to 1 in of floor Asymptomatic	Lumbar 5 left mild
None	None	Flexion to 4 in of floor Exami nation negative Asymptomatic	None
Occasional mild	None	Injured in auto accident 15 months after surgery Had re currence of symptoms and find ings Subsided in 1 month Some back pain now when working long hours under his car	Lumba 5 right mild
None	Right thigh mild	Flexion 4 in of floor	Lumbar 4 bilateral

TABLE

Correlation of Surgical Findings with

Case	Preoperative neurological findings	Surgical	
	Nerve roots involved	Mobility of free lamina	Fibrocartilaginous mass
4	Lumbar 5 sacral 1 left moderate	Marked	Bilateral
5	Lumbar 5 left moderate	Moderate	Bilateral larger on left
6	Lumbar 5 sacral 1 left moderate	Marked	Bilateral larger on left
7	Lumbar 5 right moderate	Marked	Bilateral larger on right
8	Lumbar 5 sacral 1 right moderate	Marked	Bilateral larger on right
10	Lumbar 5 sacral 1 right moderate	Marked	Bilateral larger on right
11	Lumbar 5 sacral 1 left moderate	Marked	Bilateral larger on left
12	Lumbar 5 left moderate	Marked	Bilateral larger on left
13	Right lumbar 5 moderate sacral 1 mild	Marked	Bilateral larger on right
14	Lumbar 5 bilateral moderate Sacral 1 right mild	Marked	Bilateral
15	Lumbar 5 bilateral severe Sacral 1 right moderate	Slight	Bilateral larger on right
16	Lumbar 5 right moderate	Marked	Bilateral
19	Sacral 1 right moderate	Marked	Bilateral larger on right
20	Lumbar 4 and 5 left mild	Slight	Bilateral larger on left
21	Lumbar 5 bilateral sacral 1 right moderate	Marked	Bilateral larger on left
22	Lumbar 4 and 5 bilateral moderate	Slight	Bilateral larger on right
23	Lumbar 5 sacral 1 moderate left severe right	None right but marked left	(Unilateral defect) Left small
24	Lumbar 5 bilateral worse left Sacral 1 left severe	None	Left small and posterior

1—C
Preoperative Neurological Findings

Findings

Loose ossicle at tip of pseudarthrosis	Disc pathology
Left	None
None	None
None	Protrusion lumbar 4 left
Left	None
None	Protrusion lumbar 4 right
None	None
None	None
None	None
None	None
None	None
None	None
None	None
None	None
None	None
Left	Questionable Disc material not removed
Bilateral	None
None	Herniation lumbar 4 right
Pseudarthrosis healed on right Loose ossicle present on right	None

TABLE

Case	Preoperative neurological findings	Surgical	
	Nerve roots involved	Mobility of free lamina	Fibro-cartilaginous mass
26	Lumbar 5 right moderate	Moderate	Bilateral
28	Lumbar 5 sacral 1 bilateral severe	None	Bilateral marked
29	Lumbar 5 right moderate Sacral 1 left mild	Moderate	Bilateral
31	Lumbar 5 left suggestive	None	Bilateral moderate
32	Sacral 1 left	Marked	Bilateral more on right but not compressing roots
33	Lumbar 5 right mild	Moderate	Bilateral compressing root on right
34	Lumbar 5 bilateral worse on right	Moderate	Bilateral compressing both lumbar 5 roots
35	Lumbar 5 left moderate	Marked	Bilateral larger on left
36	Lumbar 4 and sacral 1 left mild	Marked	Bilateral moderate
37	Lumbar 5 sacral 1 right moderate	Marked	Bilateral larger on right
38	Sacral 1 right mild	Moderate	Bilateral small not compressing roots
39	Lumbar 5 right moderate	Marked	Bilateral not compressing roots
40	Lumbar 5 right moderate	Marked	Bilateral
41	Lumbar 5 right severe	Moderate	Bilateral
42	Lumbar 5 bilateral worse on right	None	None Defects healed bilaterally

1—C (cont)

f n l ngs

Lo s 1 t tle of p u l rthrosis	Disc p thology
None	Lumbar 4 soft and soggy but not bulging Material excised
Right Spontaneous fusion of lumbar 5 inferior facets to sacrum	None
None	None
None	None
No loose ossicle but considerable pile up of bone at defect on right	Protrusion lumbar 5 with adherence of sacral 1 root left
No loose ossicle Spur near sacral 1 root right removed to avoid cause for future symptoms	Mild protrusion lumbar 4 Excised
None	None
None	None
None	Protrusion lumbar 4 left
No loose ossicle Lumbar 5 root right compressed by spur	None
None	Protrusion lumbar 4 and 5 left
Left	Herniation lumbar 4 right with right lumbar 5 root bound down to it
None	Complete herniation nucleus of lumbar 4 with fragments bilaterally slightl away from the midline
No loose ossicle Sharp spur down from lamina of lumbar 5 directly impaled right fifth root	Lumbar 4 soft and protruded in midline Annulus of lumbar 5 tight
No loose o si les Build up of bone at healed defects ompressed both lumbar 5 roots wor on right Spontaneous fusion lumbar 5 and sacral 1 facets left	None at this surgery Discogram 20 months later showed degeneration lumbar 3 disc and posterior herniation lumbar 4

TABLE

Case	Preoperative neurological findings	Surgical	
	Nerve roots involved	Mobility of free lamina	Fibrocartilaginous mass
43	Lumbar 5 right severe	Moderate	Bilateral not compressing roots
44	Lumbar 5 right moderate	Slight	Bilateral
45	Lumbar 5 left moderate	Marked	Bilateral very large on right
46	Lumbar 5 and sacral 1 right moderate	Marked	Bilateral small
47	Lumbar 5 and sacral 1 left	Marked	Marked on left None on right
48	Lumbar 5 bilateral mild Sacral 1 left moderate	Moderate	Bilateral small
49	None reported	Marked	Bilateral
50	Lumbar 5 and sacral 1 right	None	None No defects demonstrable Dural sac compressed by tight lamina of lumbar 5 Lamina of lumbar 5 excised but inferior facets left intact
51	Lumbar 5 bilateral worse on left Sacral 1 left mild	None	Bilateral small not compressing roots
52	Lumbar 4 and sacral 1 bilateral Lumbar 5 left	Marked	Bilateral

1—C (cont)

f d n s	
Loo o st le at s t of ps u la th ro	D c p thology
None	Herniation lumbar 4 right from which material had traveled downward about 7 mm Lumbar 5 disc normal
None	Bilateral protrusion lumbar 4
None	Protrusion lumbar 4 left
No loose ossicle Large pile up of bone at defect on right	Lumbar 4 soft but not protruding
None	Protrusion lumbar 5 right
None	Herniation lumbar 5 left Mild protrusion lumbar 4 right
None	None
None	None
No loose ossicle Right lumbar 5 root adherent at hop off between lumbar 5 and sacral 1 Solid fusion of facets lumbar 5 to sacrum	None
Right	Herniation lumbar 4 right

TABLE 1—D
Reoperation

Case	Months after decompression	Indications for reoperation	Operation and surgical findings	Result and remarks
[illegible]	115	Back discomfort and left sciatica returned when lying in bed Loss of left ankle jerk	Exploration Kinking left sacral 1 root by scar Bony over growth inferior facet lumbar 4 left	Thrown from car ninth postoperative day Wound torn open Sutured Healed per primam Nervous since Improvement moderate only
11	19	Developed coccygeal and right buttock pain SLR 70 right Left ankle jerk depressed	Exploration Meningocele 2 × 2 mm in size removed External neurolysis Marked scar about right lumbar 5 root	Flexion to level of knees Some pain behind right knee No back pain Good result
21	1 11	1 Initial excision of arch elsewhere incomplete Catching pain in back	1 Excision of fragments of loose lamina External neurolysis sacral 1 root left	1 Recurrent catching pain in back with associated clicking feeling and noise
	2 15	2 Catching in back Left sacral 1 findings	2 Excision degenerated lumbar 4 disc Adherent lumbar 5 root left	2 Improved
	3 39	3 Persistent back and left leg pain Sacral 1 findings left	3 No abnormal findings *Adhesions* fusion lumbar 4 to sacrum attempted	3 Marked improvement but continued to have some left leg pain
	4 99	4 Back pain and left leg radiation 5 in atrophy left calf Left heel jerk depressed	4 Done elsewhere Fusion not solid between lumbar 5 and sacrum	4 Mild sacral 1 findings and left lumbar 5 pain

31	1	48	1 Done elsewhere for back and left leg pain	1 Anterior interbody fusion lumbar 4 and 5	1 Failure of fusion
	2	2	2 Done elsewhere for back and left leg pain	2 Re exploration of lumbosacral area	2 Failure Patient now confined to wheel chair after this procedure
	3	63	3 Inability to carry out many former activities because of wheel chair confinement Marked restriction SLR bilaterally Persistent back pain and stiffness	3 Exploration laminectomy wound Excision of considerable scar about dural sac and nerve roots	3 Patient again ambulatory without crutches and back in college Able to swim Marked improvement in back and leg pain back motions and SLR Difficult to evaluate neurologically because of the considerable spastic paralysis of lower extremities
36		[illegible]	Re injury to back in rear end auto collision [illegible] months after surgery Developed pain left low back and left thigh numbness left foot and some left calf atrophy No improvement after exercise program	Excision of reherniated lumbar 4 disc left and some scar about the root	Last seen 78 months after original surgery Asymptomatic Neurologically negative
37	1	18	1 1 month after surgery had a fall Restriction SLR and flexion Lumbar 5 neurologic findings right Discogram 17 months later showed herniation lumbar 4 disc	1 Excision of a central protrusion lumbar 4 disc	1 Improved
	2	31	2 23 months after initial surgery had second injury Limitation SLR and back motion Stocking hypesthesia right leg Numerous other injuries	2 Excision of reherniated lumbar 4 disc right Lumbar [illegible] and sacral 1 roots bound down by scar	2 Failure Left leg pain SLR 75 right 70 left with back pain Stocking hypesthesia right leg Porphyrinuria diagnosed Conversion hysteria Attempted suicide Under psychiatric care

TABLE 1—D
Reoperation

Case	Months after decompression	Indications for reoperation	Operation and surgical findings	Result and remarks
[illegible]	115	Back discomfort and left sciatica returned when lying in bed Loss of left ankle jerk	Exploration Kinking left sacral 1 root by scar Bony over growth inferior facet lumbar 4 left	Thrown from car ninth postoperative day Wound torn open Sutured Healed per primam Nervous since Improvement moderate only
11	19	Developed coccygeal and right buttock pain SLR 70 right Left ankle jerk depressed	Exploration Meningocele 2 × 2 mm in size removed External neurolysis Marked scar about right lumbar 5 root	Flexion to level of knees Some pain behind right knee No back pain Good result
21	1 11	1 Initial excision of arch elsewhere incomplete Catching pain in back	1 Excision of fragments of loose lamina External neurolysis sacral 1 root left	1 Recurrent catching pain in back with associated clicking feeling and noise
	2 15	2 Catching in back Left sacral 1 findings	2 Excision degenerated lumbar 4 disc Adherent lumbar 5 root left	2 Improved
	3 39	3 Persistent back and left leg pain Sacral 1 findings left	3 No abnormal findings *Adkins* fusion lumbar 4 to sacrum attempted	3 Marked improvement but continued to have some left leg pain
	4 90	4 Back pain and left leg radiation 5 in atrophy left calf Left heel jerk depressed	4 Done elsewhere Fusion not solid between lumbar 5 and sacrum	4 Mild sacral 1 findings and left lumbar 5 pain

31	1	48	1 D ne el ewhere f r back an l left leg pain	1 Anterior interbody fusion lumbar 4 and 5	1 Failure of fu ion
	2	52	2 Done elsewhere f r back and left leg pain	2 Re exploration of lumbosacral area	2 Failure Patient now confined to wheel chair after this procedure
	3	53	3 Inability to carry out many for mer activites because of wheel chair confinement Marked restric tion SLR bilaterally Persistent back pain and tiffness	3 Exploration laminectomy wound Excision of considerable scar about dural sac and nerve roots	3 Patient again ambulatory with out crutches and back in college Able to swim Marked improve ment in back and leg pain back motions and SLR Difficult to evaluate neurol gically because of the considerable spastic para ly is of lower extremities
36		52	Re injury to back in rear end auto collision 12 m nths after surgery Devel ped pain left low back and left thigh numbness left fo t and some left calf atr phy No impr ve ment after exercise program	Excision of reherniated lumbar 4 disc left and ome car about the ro t	Last seen 78 months after riginal surgery Asymptomatic Neurologi cally negative
37	1	18	1 1 month after urgery had a fall Restriction SLR and flexion Lum bar 5 neurologic finding right Di ogram 17 months later showed herniation lumbar 4 disc	1 Exci ion of a central protrusion lumbar 4 disc	1 Improved
	2	31	2 3 months after initial urgery had second injury Limitation SLR and back motion St cking hypes thesia right leg Numerous other injuries	2 Excisi n of reherniated lumbar 4 di c right Lumbar 5 and sacral 1 roots b und d wn by scar	2 Failure Left leg pain SLR 75 right 70 left with back pain Stocking hypesthesia right leg Porphyrinuria diagnosed Con version hysteria Attempted ui cide Under psychiatric care

TABLE 1—D (cont.)

Case		Months after reoperation	Indication for reoperation	Operation and surgical findings	Result and remarks
40		3	Developed constant back and right leg pain Catching pain in back on arising SLR and flexion free No neurologic findings Discography of lumbar 3 advised and performed	Excision of herniated lumbar 3 disc	Good result Symptoms relieved after this procedure Has had numerous injuries since including rear end auto collisions Sustained compression fractures thoracic 9 and lumbar 1 65 months after initial surgery Has had some recurrence right low back and right calf pain but no positive neurologic findings Touches floor
41	1	9	1 Persistent severe right sciatica Local tenderness Neurologically negative Extremely nervous	1 Bilateral *Adkins* fusion attempted with iliac bone lumbar 4-5 and lumbar 5-sacral 1	1 Persistent right leg pain No definite neurologic findings
	2	18	2 Persistent right sciatica Traction on right lumbar 5 root at surgery (under local anesthesia) reproduced pain	2 Exploration revealed intra and extraneural scar right lumbar 5 root Section of sensory branch right lumbar 5 root attempted	2 Improved for several months but then had recurrence right leg pain Developed intermittent locking hyperesthesia right leg

3	39	3 N n union 1 *lkins* fusion at lumbar 4 5 level Complained of severe right sciatica Slight lumbar 5 motor deficit Slight sacral 1 sens ry deficit	3 I xpl ratic n *ldkins* fusion soll l at lumbar 5 acral 1 level I ateral *Hil l s* fusi n lumbar 4 to acral 1 attempted	1 Unimj rove l I ersistent right leg pain
4	53	4 Severe radicular pain down right sacral 1 distributi n	4 Re exploration right lumbar 5 acral 1 roots Sacral 1 rc ot clear I umbar 5 root carred considerably Fusic n solid lumbar 5 sacral 1 but not at lumbar 4 5	4 Symptoms unimproved Incon stant stocking hypesthesia entire right leg and left leg below knee
44	11	I ersistent right sciatica and left low back pain Able to touch flo r Neur l gical examinati n negative	I xploration Ring of scar about right lumbar 5 r t cuff excised	I ailure Continues to have const int back pain Mild sacral 1 findings bilaterally I ersistent pain prcbab ly due to intraneural scar formation
49	71	Asymptomatic for 5 years after ini tial decompression elsewhere and then developed low back ache and catching pain No recurrence of leg pain	I xploration I arge meningocele found di sected free and closed Some ectopic bone fc rmation pre ent Disc material exci ed at lumbar 3 an l 4 Developed wound in fection p stoperatively	C mplete relief of symptoms I xa mination negative

TABLE

Synopsis of

Case	Occupation	Length of disability (months)	Ability to resume former occupation	Length of follow up (months)	Further forward displacement and per cent of increase
4	Physician	1	Complete	144	Early first to mid first degree 9 per cent
5	Housewife	7	Complete	123	Early first to late first degree 27 per cent
6	Salesman	1	Complete	37	Early first to mid first degree 6 per cent
7	Housewife and secretary	1 5	Complete	118	None
8	Laundryman	1	*Complete*	*34*	*None*
10	Housewife	2	Complete	33	10 per cent progression of *mid first degree*
11	Secretary	10	Complete	32	None
12	Housewife	1	Complete	31	None
13	Floor covering contractor	6	Complete	112	5 per cent progression of early first degree
14	Clerk and laborer	1 5	Complete	108	3 per cent progression of early first degree
15	*Housewife*	2	*Complete*	*109*	*9 per cent progression of* early second degree
16	Clerk and housewife	1 5	Complete	118	Early first to late first degree 33 per cent
19	Medical student	1	Complete	20	None
20	Teamster	2	Complete	16	None
21	Carpenter	45	Complete	37	None
22	Marine electrician	9	Complete	97	None
23	Clerk	2	Complete	9	None
24	Janitor	4	Complete	93	None
26	Bookkeeper	5	Complete	5	None

1—E
Results

R ult	R marks
Fair	Able to spend long periods in surgery daily
Fair	Thrown from car ninth day after last surgery Wound torn open Sutured. Healed per primam Nervous since Moderate improvement only
Good	Lost from further follow up
Asymptomatic	
Asymptomatic	Lost from further follow up
Good	Lost from further follow up
Good	Lost from further follow up
Asymptomatic	Lost from further follow up
Asymptomatic	Performs all duties connected with installation of floor covering
Asymptomatic	
Good	
Asymptomatic	3 pregnancies postoperatively
As mptomatic	Lost from further follow up
Asymptomatic	Lost from further f llow up
Failure	Now emplo ed as swimming pool maintenance man Work is equally arduous according to the patient
Asymptomatic	
Fair	Lost from complete follow up
Good	
Fair	Lost from complete follow up

TABLE

Case	Occupation	Length of disability (months)	Ability to resume former occupation	Length of follow up (months)	Further forward displacement and per cent of increase
28	Bookkeeper and housewife	7	Complete	85	None
29	Shipping clerk and housewife	4	Complete	70	Early first to mid first degree 24 per cent
31	Student		Complete	87	None
32	Janitor	2	Complete	74	None
33	Painter	7 5	Complete	9	None
34	Grocery clerk	3	Complete	7	3 per cent progression of mid first degree
35	Teacher	3	Complete	79	6 per cent progression of mid first degree
36	Truck driver	4	Complete	78	5 per cent progression of mid first degree
37	Waitress and housewife	See remarks	See remarks	81	Early first to mid first degree 3 per cent
38	Waitress	9	Complete	77	None
39	Banker	4	Complete	75	None
40	Housewife and magazine sales	8	Complete	75	Early first to mid first degree 8 per cent
41	Housewife and maid	20	Partial	60	None
42	Construction worker	5	Complete	72	None

1 E (cont)

R ult	R ma k
Asymptomatic	Does own housework and laundry Holds full time job and drives 100 miles daily
Good	Developed keloid after surgery Symptoms persisted for some time but cleared after x ray therapy Able to perform work requiring lifting and wrapping of heavy packages
Failure	Classified as failure now because of operative procedures 1 and 2 on Table 1—D Markedly improved after last surgery however
Asymptomatic	73 months after surgery had recurrence of symptoms Prescribed exercise program resumed Again became asymptomatic
Failure	Felt to have a conversion hysteria Industrial litigation Obvious psychosexual abnormality Under psychiatric care Lost from complete follow up
Fair	Lost from complete follow up
Asymptomatic	Does heavy labor during summer months
Asymptomatic	
Failure	Felt to have a conversion hysteria Disability difficult to evaluate because of psychiatric problems
Asymptomatic	*Under treatment before and after surgery for numerous non related* medical problems which were cause of prolonged disability
Asymptomatic	
Good	Good result after second decompression Many postoperative injuries caused recurrence of symptoms but patient now has minimal complaints and is again considered a good result
Failure	Ability to resume occupation was complete 4 months after initial surgery but only partial after other procedures
Fair	Returned to lighter work 5 months after surgery but later resumed regular job 17 months after surgery had onset of new symptoms Disc excision advised but patient has not wished surgery Does extremely heavy work 15 hrs per day

TABLE

Case	Occupation	Length of disability (months	Ability to resume former occupation	Length of follow up (months)	Further forward displacement and per cent of increase
43	Assembly worker	4	Complete	57	None
44	Housewife	8	Complete	68	9 per cent progression of early first degree
45	Housewife	3	Complete	56	None
46	Brushmaker and housewife	4	Complete	40	None
47	Automobile painter	5	Complete	34	Early first to mid first degree 9 per cent
48	Housewife Very athletic	2	Complete	32	None
49	Welder	8	Complete	96	7 per cent progression of mid first degree
50	Student	3	Complete	24	Mid first to late first degree 22 per cent
51	Student	2	Complete	23	Nominal fourth to true fourth degree after surgery
52	Farmer	See remarks	See remarks	4	None

Asterisk indicates those patients who had operative procedures following the initial decompression Disability indicated is accrued total resulting from all operative procedures

Definition of terminology describing degree of displacement

Spondylolysis = No measurable degree of displacement

First degree = Slipping from 1 to 50 per cent
Early = 1 to 17 per cent
Mid = 18 to 35 per cent
Late = 36 to 50 per cent

1 E (cont)

R sult	Rem rks
Good	Herniated disc probable sole cause of symptoms 2 years after surgery developed right lower quadrant pain History of intermittent claudica tion Aorta calcified Myelo ram and discogram not remarkable 2/ months after surgery
Failure	Persistent pain in low back and right calf Unimproved following second operation
Good	Asymptomatic and dismissed from care 3 months after surgery Fell 31 months after surgery and had recurrence of mild back and left leg pain Now classified as good because of the occasional right buttock pain which appeared subsequent to this injury
Good	Rear end auto collision 13 months after surgery Developed mild back ache after this injury
Fair	Good result until auto accident 15 months after surgery Now con sidered fair
Asymptomatic	2 months after surgery had acute recurrence after swimming with flippers S mptoms subsided completel after rest and caudal injections Continues to be very athletic now
Asymptomatic	
Asymptomati	
Good	Has o casional mild backache after working under his car for pro longed periods of time
Good	Patient had not returned to work when last seen No financial need to do so Lost from complete follow up

Second degree	= Slipping from 51 to 99 per cent
Early	= 51 to 68 per cent
Mid	= 69 to 86 per cent
Late	= 87 to 99 per cent
Third degree	= Slipping of 100 per cent
Fourth degree	= *Slipping of 100 per cent plus resting of the inferior* aspect of the body of the involved vertebra against the anterior aspect of the vertebra below

TABLE

Synopsis of Patients with Previous Fusion Treated

Case	Sex	Age	Occupation	Duration of symptoms (years)	Level and degree of displacement
1	F	21	Waitress and housewife	6	Lumbar 5 first
2	F	42	Bookbinder and housewife	11	Lumbar 5 first
3	F	21	Secretary and housewife	10 worse past 3 years	Lumbar 5 first
9	F	37	Housewife	23	Lumbar 5 first
17	F	34	Housewife	7	Lumbar 5 first
18	F	24	Secretary and housewife	12	Lumbar 5 first
25	F	26	Housewife	Many years	Lumbar 5 first
27	F	37	Mail house order clerk and housewife	Severa year	bar 5 irst
30	F	3[illegible]	Maid and housewife	4	ar

2—A

by Excision of the Loose Arch and Decompression

Previous surgery	Degree of disability before decompression
Excision of loose arch alone and fusion with iliac bone by Dr Gill in 1949	Total
Excision of loose arch and decompression lumbar 5 nerve roots bilaterally followed by fusion with iliac bone lumbar 4 to sacrum by Dr Gill in 1950 Patient had had no back surgery prior to this	Total
Hibbs fusion with iliac bone lumbar 4 to sacrum by Dr Gill Thrombophlebitis was postoperative complication	Moderate
First fusion 1950 failed Coccygectomy 1950 Second fusion 1951 failed All done elsewhere	Total
First fusion 1949 failed Second fusion 1951 failed Both done elsewhere	Total
Exploration and fusion lumbar 4 to sacrum 1950 failed Second fusion 1951 failed Third fusion 1952 failed All done elsewhere	Total
First fusion 1951 failed Second fusion 1952 Done elsewhere Did fairly well for 7 or 8 months after second fusion but had recurrence of symptoms after moving furniture	Total
3 attempted fusions lumbar 3 to sacrum done elsewhere 1939 1940 1942 Last fusion reportedly successful	Total
Fusion of lamina of lumbar 4 to spinous process and lamina of lumbar 5 1952 No apparent attempt at fusion between lumbar 3 and 4 Done elsewhere	Total

TABLE
Comparison of Symptoms and Findings

Preoperative				
Case	Back pain	Area of radicular pain	Abnormal physical findings	Nerve roots involved
1	Constant severe	Both calves severe on right	Flexion to 6 in of floor Extension limited and painful	Lumbar 5 sacral 1 bilateral moderate
2	Constant severe	Right lower extremity severe	Flexion to 6 in of floor with pain in right low back SLR to 65 on right and 30 on left *Tenderness to palpation lumbosacral junction*	Lumbar 5 sacral 1 left moderate
3	Moderate	Left leg moderate	Some restriction SLR Tender over loose arch Pain on extension	None
9	Constant moderate	Coccyx moderate left sciatica severe	Flexion to 5 in of floor SLR 90 right 70 left	Lumbar 5 left moderate
17	Constant severe	Both thighs and calves moderate	Flexion to 5 in of floor with reproduction of right sciatica Extension limited and painful	Lumbar 5 bilateral marked on right
18	Constant severe	Right buttock and sciatica severe	Flexion to knees Extension restricted and extremely painful causing right sciatica SLR 70 bilaterally	Lumbar 5 bilateral marked on right Sacral 1 right moderate
25	Constant severe	Left leg	Tender over graft donor site Flexion to 8 in of floor Extension restricted Stocking hypesthesia entire left leg	Lumbar 5 left moderate

ª—B
before and after Decompression Operation

Postoperat ve m s recent exam na n			
Back pain	Area of radicula pa n	Abn rmal physical f n l ngs a l rem k	N r re s m f
M ld, only after heavy work. Morning stiff ness relieved by exercise	Right calf occasi nal, mild	Slight tightness f SLR n right	Sacral 1 right mild
Aching mild	Coccyx and right leg mild	Limitation of flexion to le el o knees Neurol gi al examina i n negative Fu ion olid	N ne
Aching after heavy work	Occasional left calf pain	SLR free Some back tenderne and discomfort n exten i n Flexes to t u h floor X ray e iden e of degenerati n and p terior al ifi ati n at lumbar 4 disc Fu ion solid at lumbar 4 P eudarthro i at lumbar 5	N ne
Tired feeling after prolonged itting	N ne	Touches fl r Examination negative	N ne
Feeling of weakness	Right calf mild	Exten i n lightly painful. Tou hes metacarpal head to fl r	N ne
Mild. occa ional	Ri ht iati a mild, occasional	Tou hes floor SLR free Back and leg disc mf rt now are a sociated mainl with men trual period Some ti htness in back at end f day Re-operated. See Table 2—D	Sacral 1 right mild
Tender over perative area	Ri ht leg	D ing well until 2 weeks prior to last examination when she fell on buttocks. See Table 2—E	Lumbar 5 bilateral, mild

TABLE

Preoperative				
Case	Back pain	Area of radicular pain	Abnormal physical findings	Nerve roots involved
27	Severe	Aching left leg Severe pain right leg	Marked restriction and pain on SLR Flexion to 10 in of floor Had large adherent stellate scar over sacrum from pressure of cast worn after the fusion	Lumbar 4 right Lumbar 5 sacral 1 bilateral
30	Constant	Coccyx and both legs severe	Walked in flexed position with upper lumbar area hyperextended Generalized hypesthesia right leg	Lumbar 5 bilateral mild

2—B (cont)

Postoperative (most recent examination)			
Back pain	Area of radicular pain	Abnormal physical findings and remarks	Nerve root involved
Dull ache on left	Aching in left leg	Flexion to 2 in of floor SLR 90 bilaterally Plastic correction of scar strongly advised See Table 2—D	Sacral 1 left mild
Catching occasionally	None	Reoperated See comments on Table 2—D Was asymptomatic and negative 4 days prior to injury described on Table 2—D Recently developed catching in back. *Flexion free but slight* two stage recovery	Sacral 1 left mild

TABLE

Correlation of Surgical Findings with

Case	Preoperative neurological findings	Surgical	
	Nerve roots involved	Level of pseudarthrosis	Amount of motion at defect in pars interarticularis of involved vertebra
1	Lumbar 5 sacral 1 bilateral moderate	Lumbar 4 and 5 Lumbar 5 and sacral 1	Perceptible only after removal 0 25 in of bone
2	Lumbar 5 sacral 1 left moderate	None	Marked
3	None	Fusion solid	None
9	Lumbar 5 left moderate	Lumbar 4 and 5 Lumbar 5 and sacral 1	Barely perceptible
17	Lumbar 5 bilateral marked on right	Lumbar 4 and 5 Lumbar 5 and sacral 1	Barely perceptible
18	Lumbar 5 bilateral marked on right Sacral 1 right moderate	Lumbar 4 and 5 Lumbar 5 and sacral 1	Barely perceptible only after removal 0 25 in of bone
25	Lumbar 5 left moderate	Frank nonunion at lumbar 4-5 and lumbar 5-sacral 1 with overgrowth of bone above lamina of lumbar 4 which buttressed against spinous process of lumbar 3 Numerous fragments of bone over surface of fusion mass	Barely perceptible
27	Lumbar 4 right Lumbar 5 and sacral 1 bilateral	Nonunion at lumbar 3 Questionable nonunion at lumbar 5 Little motion present however	Barely perceptible
30	Lumbar 5 bilateral mild	Lumbar 4-5	Barely perceptible

2—C
Preoperatie \eurological Findinjs

fin lin ŗs

F b ca l l ri ious a	Disc p tholo \ ar d fur l mt r n
Bilateral larger on right	Fusion mass extended over lamina of lumbar 4 and com pressed dura
Bilateral compressing both lumbar 5 roots	\o disc patholog\
Present on left	\one noted
Bilateral larger on left	\one noted
Bilateral larger on right with adhesions to lumbar a root right	Dura compressed by sinking in of fusion mass
Bilateral larger on right	Dura compressed b mass of ligamentum flavum below lamina of lumbar 3
Bilateral larger on left with compression left lumbar 5 root Right lumbar 5 root clear	Adhesions under graft to dura Considerable ligamentum flavum present Lumbar 5 disc markedl\ collapsed Impossi ble to remove di c material Lumbar 4 disc normal
Bilateral and compressing both lumbar a roots	Lumbar 3 disc degenerated bogg and bulging Lumbar 4 and 5 discs normal
Bilateral	Luml ar 4 dis pr minent on right Lumbar a disc collapsed

TABLE
Synopsis of

Case	Occupation	Length of disability (months)	Ability to resume former occupation	Months of follow up after decompression	Further forward displacement and per cent of increase**
1	Waitress and housewife	4	Complete	24	None
2	Bookbinder and housewife	28	Complete	114	Early first to late first degree 25 per cent
3	Secretary and housewife	3	Complete	146	None
9	Housewife	7	Complete	32	None
17	Housewife	2	Complete	28	None
18	Secretary and housewife	8 5	Complete	113	Early first to mid first degree 15 per cent
25	Housewife	3	Complete	9	Early first to mid first degree 19 per cent
27	Mail house order clerk and housewife	7	Complete	95	4 per cent progression of early first degree
30	Maid and housewife	18	Complete	86	None

Asterisk indicates those patients who had operative procedures following the initial decompression Disability indicated is accrued total resulting from all operative procedures

Definition of terminology describing degree of displacement

Spondylolysis — No measurable degree of displacement

First degree — Slipping from 1 to 50 per cent
Early — 1 to 17 per cent
Mid — 18 to 35 per cent
Late — 36 to 50 per cent

?—C
Preop rative Neurological Findin js

findin s	
F broca t la n us ma	Di patholo y a d lural ompr s n
Bilateral larger on right	Fusion mass extended over lamina of lumbar 4 and compressed dura
Bilateral compressing both lumbar 5 roots	No disc pathology
Present on left	None noted
Bilateral larger on left	None noted
Bilateral larger on right with adhesions to lumbar 5 root right	Dura compressed by sinking in of fusion mass
Bilateral larger on right	Dura compressed by mass of ligamentum flavum below lamina of lumbar 3
Bilateral, larger on left with compression left lumbar 5 root Right lumbar 5 root clear	Adhesions under graft to dura Considerable ligamentum flavum present Lumbar 5 disc markedly collapsed Impossible to remove disc material Lumbar 4 disc normal
Bilateral and compressing b th lumbar 5 roots	Lumbar 3 disc degenerated boggy and bulging Lumbar 4 and 5 discs normal
Bilateral	Lumbar 4 disc prominent on right Lumbar 5 disc collapsed

TABLE 2—D
Reoperations

Case		Months after operation	Indication for reoperation	Operation and surgical findings	Result and remarks
2	1	5	1 3 months after surgery developed severe pain over operative area with radiation to right buttocks and coccyx X rays showed shifting of grafts toward midline over dura	1 Exploration Excision of thick scar between dura and graft Excision of bone chips compressing terminal end of spinal theca	1 Relief of coccygeal and right leg pain for about six weeks
	[illegible]	14	2 Recurrence of coccygeal and right leg pain	2 Exploration Excision of thick scar over dura Excision of adhesions between right sacral 1 root and wall of canal also between pedicle of lumbar 5 and right fifth lumbar nerve root Refusion with rib grafts lumbar 4 to sacrum	2 Fusion solid Right leg pain disappeared Neurological examination continued to be normal
	3	38	3 Recurrence of coccygeal pain	3 Exploration Fusion solid Excision thin scar about dura and right sacral 1 root Small dural arachnoid cyst found	3 Patient had spinal fluid fistula for 4 to 5 weeks after surgery Temporary relief of symptoms only although neurological examinations have remained negative
18	1	8	1 Aching in back and local soreness Some pain right buttocks No leg pain X ray evidence of new bone formation about previous fusion site	1 Exploration Excision of osseous proliferation in scar overlying dural sac	1 Much improved Free back motion No radicular pain 1 month after surgery was struck in back by doorknob Developed soreness over sacrum and later radicular pain int right buttock and leg

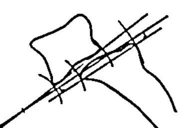
	13	2	Per l tent l acl a l wit l a lia tion to coccyx Sacral 1 findings left Slight pa m on back moti n	?	l jl rati n l x l i n of al out lura an l r ght luml a 5 a d sacral 1 ro ts Exci ion of degenerated disc material at lumbar 4	–	Inp vel Continu l t have son c back and right leg j ain Became pregnant 7 months later Had some increase in back pain but pregnancy and delivery much easier than with other child Did very well afterward Essentially lost back pain and had only mild right leg discomfort
3	68	3	4 months previously slipped and twisted back Had recurrence of back and right leg pain Mil l lumbar 5 and sacral 1 findings right Discogram howed protru sion at lumbar right	3	I xploration I reeing of right lumbar 5 root which was bound to annulus of lumbar 5 disc by car I xcisi n of disc material at lumbar 5	3	Improved but continued to have some back and right leg discom fort Injured 3 years later while water skiing Had some increase in symptoms Mild lumbar 5 findings present on right
4	110	4	3 months before surgery had belly flop while water kiing Developed more right leg j ain Later deve loped 5 in atrophy right calf and cme right lumbar o neurol gi changes	4	Rehernation lumbar 4 disc right	4	I ast seen 3 5 months after sur gery Calves equal No sensory changes Right heel jerk dimin ished Much improved Consider ed as fair result
?7	31		Unhealed ulcer and large adherent stellate scar ver sacrum caused by pres ure of ca t worn after fu sion		Biop y cf scar No malignancy No infection Scar exci ed Tran p l tion of gluteal skin flap perf rmed D ne el ewhere at our recommenda tion		I xcellent
30	1 15	1	7 months after decompression fell on buttocks Devel oped in ability to straighten bacl and j aresthe ias in feet Bizarre pos ture SLR free I lexi on to 2 in of fl oor Neurologically negative	1	I xplorati on Done el ewhere Adhe ions reporte l	1	Developed wound infection Seen by us 2 years later Had stock ing hype thesia left leg No re flex or motor abn rmality No atrophy SLR free Dia tasis of pinalis mu cles Considerable back stiffnes

TABLE 3

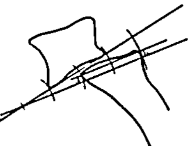
Case 5 Female Birth Date 6 15 41 Date of Surgery 11 5 51



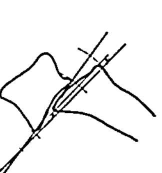
8 26 46 17 ∠



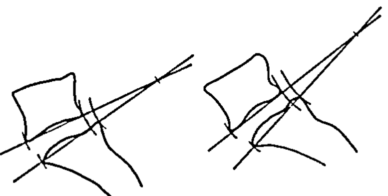
6 30 53 14 ∠



11 5 53 18 ∠

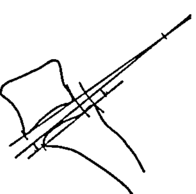


1 4 55 23 ∠

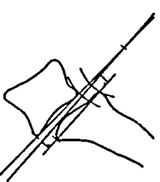


8 23 55 38 ∠

7 10 56 46 ∠



8 12 58 50 ∠



11 16 61 44

TABLE 4

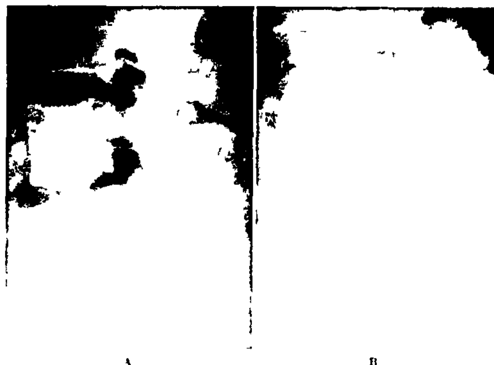
Postoperative Progression of Displacement According to Age

Age at surgery (years)	Number of Patient		Average postoperative progression of displacement	
	(Males)	(Females)	(Males)	(Females)
25 or under	1	4	3%	19%
26 to 30	0	2	0%	23%
31 to 35	1	0	5%	0%
36 to 40	4	3	5%	5%
41 to 45	1	2	9%	17 5%
46 to 50	1	1	7%	24%
51 to 55	0	1	0%	9%
56 to 60	1	0	9%	0%

TABLE 5

Postoperative Progression of Displacement According to Sex

	Number of patients	
	Males	Females
Sex of patients	21 (40 4%)	31 (59 6%)
Patients with postoperative progression of displacement	9 (42 8%)	13 (41 9%)
Average displacement in patients with post operative progression of displacement	9 (5 9%)	13 (16 0%)
Average follow up in all patients	21 (62 months)	31 (65 months)
Average follow up in patients without post operative progression of displacement	12 (51 months)	18 (56 months)
Average follow up in patients with post operative progression of displacement	9 (77 months)	13 ([illegible]9 months)



A B

Fig 1 Case 2

A Roentgenogram four months before a combined decompression and fusion in a forty two year old female

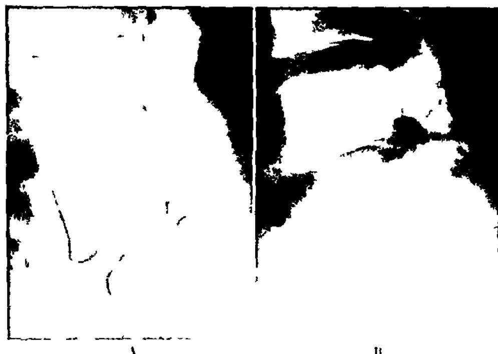
B Roentgenogram 114 months after surgery shows a 25 per cent progression of the first degree spondylolisthesis



Fig 2 Case 3

A Roentgenogram ten months prior to the decompression operation in a twenty one year old female Re exploration because of persistent symptoms showed solid fusion from lumbar 4 to the sacrum and a decompression was done on the left (The roentgenogram has been retouched)

B Roentgenogram 146 months after the decompression pro edure There has been no progression of displacement despite the pseudarthrosis at the 5th lumbar interspace



A B

Fig 3 Case 4

A Roentgenogram eleven months before the decompression operation in a forty-one year old male (The roentgenogram has been retouched)

B Roentgenogram 144 months after surgery shows a 9 per cent progression of the first degree spondylolisthesis (The roentgenogram has been retouched)

Fig 5 Case 7 →

A Roentgenogram immediately prior to the decompression operation in a twenty three year old female (The roentgenogram has been retouched)

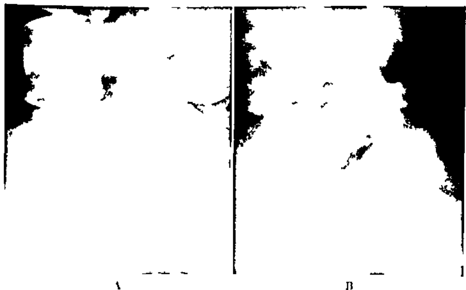
B Roentgenogram 118 months after surgery shows no progression of displacement The roentgenogram has been retouched)

A B

Fig 4 Case 5

A Roentgenogram sixty two months before the decompression operation in a woman thirty years of age at the time of surgery

B Roentgenogram 123 *months after surgery* shows a 27 *per cent progression* of the first degree spondylolisthesis



A B

Fig 5 Case 7



A B

Fig 19 Case 19

A Roentgenogram before the decompression operation in a thirty eight year old female (The roentgenogram has been retouched)

B Roentgenogram eighty five months following surgery shows no progression of displacement (The roentgenogram has been retouched)

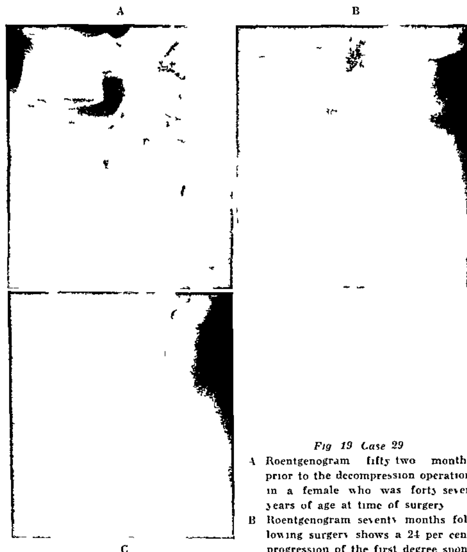
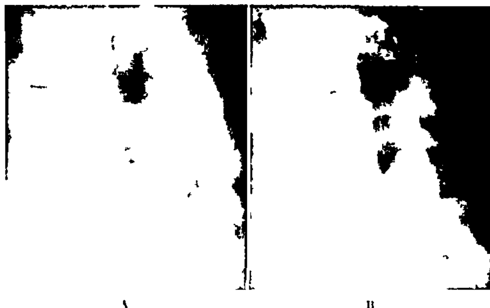


Fig 19 Case 29

A Roentgenogram fifty two months prior to the decompression operation in a female who was forty seven years of age at time of surgery

B Roentgenogram seventy months following surgery shows a 24 per cent progression of the first degree spondylolisthesis (The roentgenogram has been retouched)

C *Roentgenogram seventy months following surgery In this film sand bags weighing twenty four pound were placed on the patient s shoulders* but no essential change in the position of the body of the fifth lumbar vertebra is noted with this added weight (The roentgenogram has been retouched)



A B

Fig. 20. Case 30

A. Roentgenogram thirteen months before the decompression operation in a female who was thirty-two years of age at the time of surgery. There is a first degree spondylolisthesis of the fourth lumbar vertebra. Two years previously a fusion from the fourth lumbar vertebra to the sacrum was attempted elsewhere and resulted in pseudarthrosis.

B. Roentgenogram eighty-six months following the decompression shows no progression of displacement.



A B

Fig. 21. Case 31

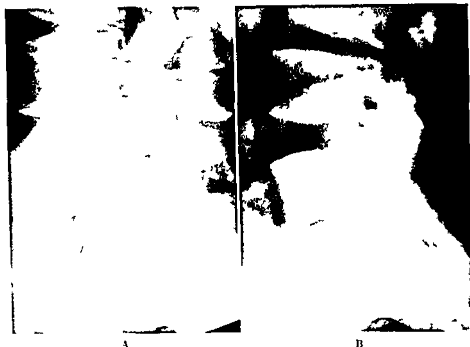


Fig 22 Case 32

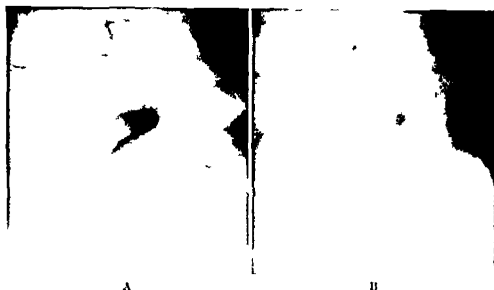
A Roentgenogram four months prior to the decompression operation in a fifty one year old male (The roentgenogram has been retouched)

B Roentgenogram seventy four months following surgery shows no progression of displacement (The roentgenogram has been retouched)

← *Fig 21 Case 31*

A Roentgenogram twenty one months prior to the decompression operation in a woman who was twenty one ears of age at the time of surgery (The roentgenogram has been retouched)

B Roentgenogram eighty three months following the decompression procedure Interbody fusion at the fourth and fifth lumbar levels was attempted elsewhere forty eight months following the initial surgery and resulted in pseudarthrosis No progression of displacement has occurred (The roentgenogram has been retouched)



A B

Fig. 3 Case 33

A. Roentgenogram immediately prior to the decompression operation in a thirty-seven year old male (The roentgenogram has been retouched)

B. Roentgenogram seven months following surgery shows a 3 per cent progression of the first degree spondylolisthesis. (The roentgenogram has been retouched)



A B

Fig. 4 Case 35



A B

Fig 25 Case 36

A Roentgenogram immediatel prior to the decompression operation in a thirty eight year old male (The roentgenogram has been retouched)

B Roentgenogram seventy eight months following surgery shows a 5 per cent progression of the first degree spondylolisthesis

---

← *Fig 24 Case 35*

A Roentgenogram three months following the decompression operation in a thirty six year old male Preoperative roentgenograms were not available (The roentgenogram has been retouched)

B Roentgenogram seventy nine months following surgery shows a 6 per cent progression of the first degree spondylolisthesis



A B

Fig [illegible]3. Case 3[illegible]

A Roentgenogram immediately prior to the decompression operation in a thirty-seven year old male. (The roentgenogram has been retouched.)

B Roentgenogram seven months following surgery shows a 3 per cent progression of the first degree spondylolisthesis. (The roentgenogram has been retouched.)



A B

Fig [illegible]4. Case [illegible]



Fig ?8 Case 39

A Roentgenogram two months following the decompression operation in a forty five year old male Preoperative roentgenograms were not available (The roentgenogram has been retouched)

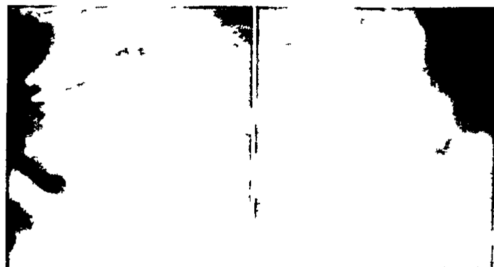
B Roentgenogram seventy five months following surgery There has been no progression of displacement (The roentgenogram has been retouched)

A B

Fig. 9. Case 10

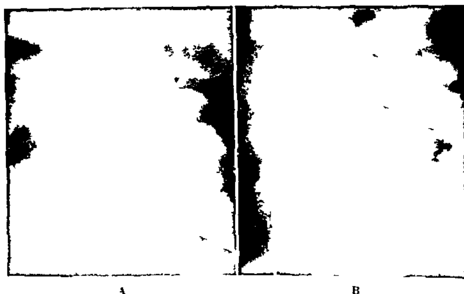
A. Roentgenogram immediately prior to the decompression operation in a thirty-six-year-old female. (The roentgenogram has been retouched.)

B. Roentgenogram seventy-five months following surgery shows an 8 per cent progression of the first degree spondylolisthesis. (The roentgenogram has been retouched.)



A 1

Fig. [illegible] Case 11



A B

Fig 31 Case 3

A R entgenogram immediately prior to the decompression operati n in a forty seven year old male

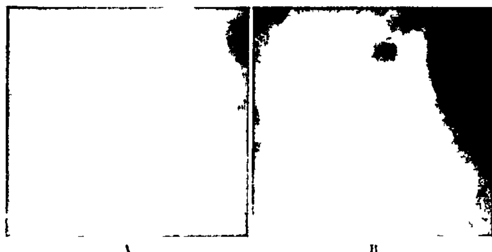
B Roentgenogram seventy two months following surgery shows no progression of displacement

←

Fig 30 Case 41

A Roentgenogram two months before the decompression operation in a thirty year old female (The roentgenogram has been retouched)

B Roentgenogram sixty months after surgery shows no progression of displacement



A B

Fig 52 Case 43

A Roentgenogram one month prior to the decompression operation in a fifty seven year old female (The roentgenogram has been retouched)

B Roentgenogram fifty seven months following surgery shows no progression of displacement (The roentgenogram has been retouched)



A B

Fig 53 Case 44

A Roentgenogram fifty three months prior to the decompression operation in a woman who was fifty five years of age at the time of surgery (The roentgenogram has been retouched)

B Roentgenogram sixty eight months after surgery shows a 9 per cent progression [illegible]

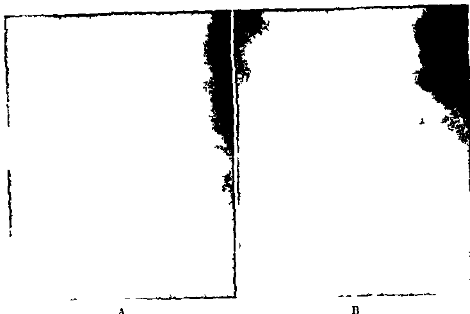


Fig 34 Case 45

A Roentgenogram shortly before the decompression operation in a fifty seven year old female (The roentgenogram has been retouched)

B Roentgenogram fifty six months after surgery shows no progression of displacement

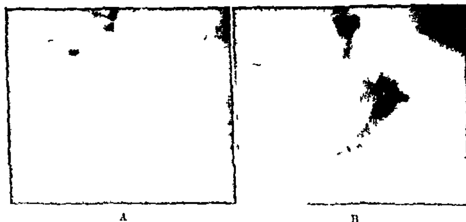


Fig 35 Case 46

A Roentgenogram two months before the decompression operation in a twenty ni year old female (The roentgenogram has been retouched)

B Roentgenogram forty months following surgery shows no n of d placement

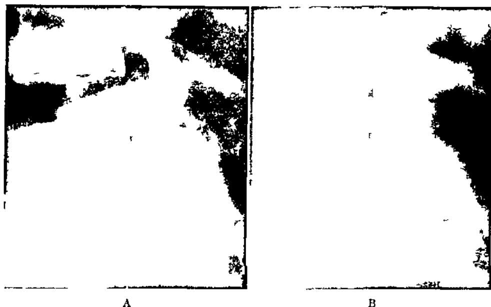


Fig 36 Case 47

A Roentgenogram two years prior to the decompression operation in a male who was fifty seven years of age at the time of surgery

B Roentgenogram thirty four months after surgery shows a 9 per cent progression of displacement

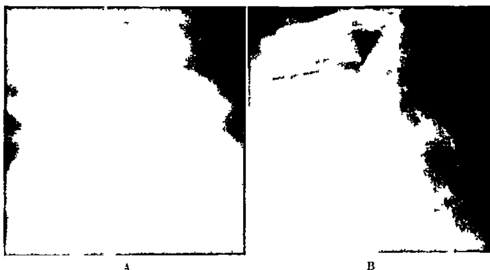


Fig 37 Case 48

A Roentgenogram nine months prior to the decompression operation in a forty six year old female

B Roentgenogram thirty two months after surgery shows no progression of displacement

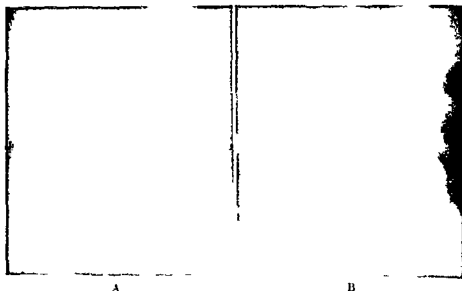


Fig 38 Case 4J

A Roentgenogram immediately prior to the decompression operation in a forty eight year old male There is a first degree spondylolisthesis of the fourth lumbar vertebra (The roentgenogram has been retouched)

B Roentgenogram ninety six months following surgery shows a 7 per cent progression of displacement (The roentgenogram has been retouched)



Fig 39 Case 50

A Roentgenogram thirteen months before the decompression operation in a girl who was fourteen years of age at the time of surgery (The roentgenogram has been retouched)

B Roentgenogram two months before surgery shows no progression of displacement

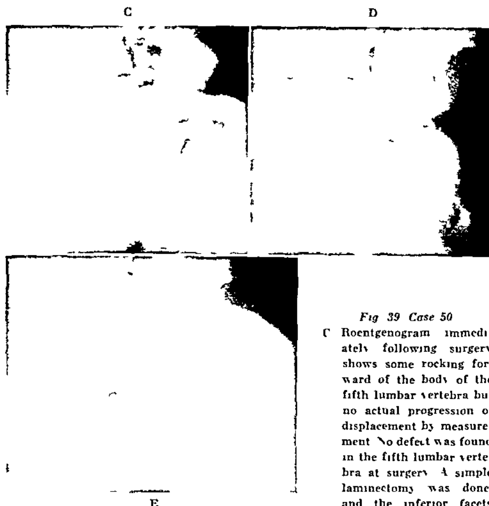


Fig 39 Case 50

C Roentgenogram immediately following surgery shows some rocking forward of the body of the fifth lumbar vertebra but no actual progression of displacement by measurement No defect was found in the fifth lumbar vertebra at surgery A simple laminectomy was done and the inferior facets were left intact

D Roentgenogram nine months following surgery still shows no progression of displacement

E Roentgenogram twenty four months after surgery shows a 22 per cent progression of displacement

---

Fig 40 Case 51 →

C Roentgenogram two months prior to the decompression operation now shows a *fourth degree spondylolisthesis of the fifth lumbar vertebra (The roentgenogram* has been retouched)

D Roentgenogram one month following the decompression operation At surgery solid healing of the defect in the pars interarticularis on the left and spontaneous fusion of the inferior facets of the fifth lumbar vertebra to the superior facets of the sacrum bilaterally were found (The roentgenogram has been retouched)

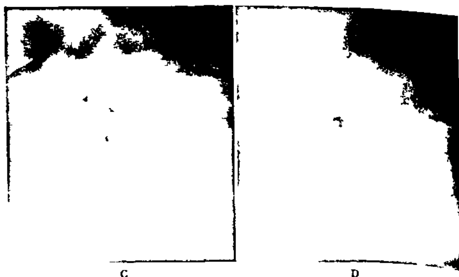


A B

Fig 40 Case 51

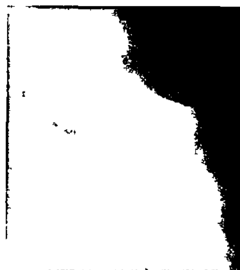
A Roentgenogram twenty six months before the decompression operation in a b y who was fourteen years of age at the time of surgery (The roentgenogram has been retouched)

B Roentgenogram sixteen months prior to surgery shows continued progression of displacement (The roentgenogram has been retouched)



C D

Fig 40 Case 51



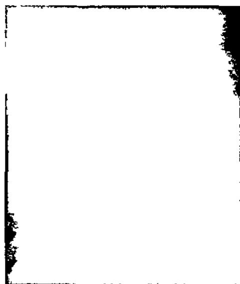


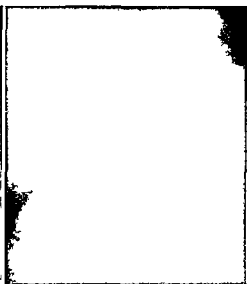
E F

Fig 40 Case 51

E Roentgenogram eighteen months after surgery (The roentgenogram has been retouched)

F Roentgenogram twenty three months after surgery (The roentgenogram has been retouched)





A B

Fig 41 Case 52

A Roentgenogram immediately prior to the decompression operation in a fifty two year old male There is a first degree spondylolisthesis of the fourth lumbar vertebra

B Rc ntgenc gram f ur months following surgery shows no progression of dis placement

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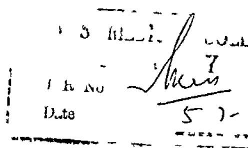
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JOHANNES MEYER

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Supplementum N
Munksgaard Co

Treatment of
Legg Calve Perthes Disease

ACTA ORTHOPAEDICA SCANDINAVICA
SUPPLEMENTUM NO 86

Treatment of Legg-Calvé-Perthes Disease

Assessment of Therapeutic Results with Particular Reference to the Value of Traction in Bed

By

JOHANNES MEYER

MUNKSGAARD
COPENHAGEN 1966

Preface

The present study was carried out in the Seaside Hospital Refsnæs My thanks go to the management for the good working conditions which I have enjoyed and for financial aid towards the publication

I should like to thank also the staff in the Seaside Hospital Refsnæs and in the Finsen Institute Copenhagen for their ever ready help in the course of the study In particular I want to thank my X ray assistant Mrs *Agnethe Back* The reading and measurement of the numerous films would not have been possible without Mrs *Back s* unfailing interest and understanding of the problems involved

For the statistical calculations and discussions concerning statistical problems I am indebted to *Svend Sorensen* M A (econ)

Kysthospitalet pa Refsnæs pr Kalundborg Denmark

January 1966

Johannes Meyer

Contents

Introduction

In 1909–1910 almost simultaneously Jaques Calve Arthur T Legg Georg Perthes and Henning Waldenstrom described a new syndrome which affected children and which was caused by pathological changes in the femoral head

As the nature of this disease was unknown it was named during the subsequent years after one of these four authors In English speaking countries it is now generally known as Legg Calve Perthes disease (LCPD) and this term will be used in the present publication

The description of this new syndrome meant that these cases—which had previously been interpreted and treated as tuberculosis—could now be distinguished as a disease *per se* of a far more benign course than tuberculosis of the hip joint The long lasting and difficult treatment which had been used previously in the belief that the condition was a tuberculous manifestation was now superfluous and could be replaced by a far gentler management

But then it changed to the other extreme The patients were left practically untreated—apart from periodical short lasting relief from weight bearing when the children had pain (symptomatic treatment) It was believed that the disease ran a completely regular course regardless of any therapeutic measures

This point of view was also accepted in Denmark

The first reports on LCPD in Denmark came from Sundby Hospital Copenhagen in March 1914 (Flemming Møller) and from the Seaside Hospital Refsnæs in September 1914 (Michelsen) During the subsequent decades the patients in this country too received only symptomatic treatment or none

Gradually however it was realized in Denmark as well as in other countries that the prognosis of untreated LCPD was not as favourable as assumed True the majority of patients were symptom free immediately after the lesions had healed but the X ray film showed that often the head was considerably deformed—flat mushroom shaped—

and later many cases developed severe secondary osteoarthritis of the hip causing severely disabling symptoms

More active measures appeared to be indicated and in the course of the 1930'ies better results from long lasting non weight bearing—in some cases with traction—were reported from England (Danforth 1934 Eyre-Brook 1937)

In Denmark it was suggested by Hans Friderichsen as early as 1933 that the patients be treated by long lasting bed rest This form of treatment was adopted in 1940 at the Seaside Hospital Refsnæs where LCPD had been treated only symptomatically since 1914

In 1952 the results of this treatment were analysed by Helbo and compared with those of symptomatic—or no—treatment in a series whose main part had been published by Flemming Møller in 1924

Helbo concluded that long lasting relief from weight bearing was a definite advance compared with symptomatic treatment He did not state his opinion as to which form of long lasting relief from weight bearing was to be preferred

This problem was tackled by Mose in 1964

He analysed 2 series treated by long lasting bed rest in the Seaside Hospital Refsnæs and the Hospital for Physical Medicine and Rehabilitation Hornbæk during the period 1953–1957 The treatment had not been entirely identical as a more intensive physical therapy and exercise therapy had been used in Hornbæk The results obtained in these two series were then compared with those of ambulatory relief from weight bearing by a Thomas walking brace in two orthopaedic departments in Jutland (Sønderborg and Kolding)

Mose concluded that long lasting relief from weight bearing by recumbency afforded definitely better results than ambulatory relief from weight bearing by a Thomas walking brace The difference was statistically significant

As the results appeared to be the better the more effective the relief *from weight bearing* we started combining the long lasting recumbency with traction applied to the legs in the Seaside Hospital Refsnæs

By now it ought to be possible to assess the results of this traction therapy However when the author started analysing the result he came across problems which had to be solved if the assessment was to be reliable

In the two studies mentioned above Helbo's and Mose's the assessment had been done by different principles—clinical and radiological—so that a direct comparison of the results from these two

studies mutually and with those obtained by traction proved impossible

First and foremost then it was necessary to arrive at the most rational method for assessing the results achieved in the treatment of LCPD By application of this method first to the assessment of the traction series and then to series treated by other methods it ought to be possible to obtain a reliable evaluation of the different therapeutic methods

It was this task which the author set himself in the present study

It is based in large measure upon the reports of Helbo and Mose primarily because these two monographs are *far more detailed* and *better substantiated* than papers published in periodicals in the usual form and of the usual extent Both are accompanied by brief case histories for each individual patient This renders it possible to assess critically the authors conclusions and analyse the published materials from different angles

Moreover a considerable part of both series is derived from the Seaside Hospital Refsnæs so that the present author is thoroughly familiar with the performance of the treatment and has access to all the X rays obtained in the course of the treatment and later during the follow up

All these factors make the two studies particularly well suited to form—together with the subsequent study performed in the Seaside Hospital Refsnæs—the basis of the present study which may in fact be considered a continuation of Helbo s and Mose s

As their reports dealt with a number of problems of *no* interest in this connection they will not be reviewed *in toto* Those parts of the two monograph which are of interest will be reviewed gradually as they become of topical interest to the present subject

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the epiphysis in the irregular angular heads and such measurement cannot be performed in a sensible way (Mose)

Herndon & Heymann have tried to improve the radiological measuring methods by measuring also the deformity of the acetabulum and of the femoral neck after the treatment However this method is so complicated including so many poorly defined measurements that its performance can only be inaccurate and its significance is difficult to evaluate (*vide infra*)

Jonsater measured the height and width of the head on arthrographic exposures but this method suffers from the same disadvantage as Herndon and Heymann's It is inaccurate as it is difficult to state the exact site where the head is broadest Therefore the measurement of the height of the head will become inaccurate As a measure of its shape it is on the whole insufficient

As will gradually appear from the following several weighty objections may be raised to all these clinical and radiological methods of assessment Owing to these imperfections there is a complete lack of agreement between the therapeutic results reported in the literature The number of successful results of apparently the same therapeutic method varies in the reports by the various authors from *a few* to 100 per cent (Mose) These disagreements are not due exclusively to difficulties connected with and imperfections of the studies performed at the time of primary healing The explanation is largely that the results are not directly related to the final clinical result but serve merely as a basis for a tentative long term prognosis

If a method for treating LCPD is to be assessed the problem is to predict—a year or two after the treatment has been completed—which symptoms the patient is likely to have at the end of 25 years or more when secondary osteoarthritis really sets in It is the frequency of these late symptoms which decides whether or not a therapeutic method may be called successful while the symptoms at the time of primary healing are of relatively little importance

However such a prediction has proved at least as difficult and subjective as the evaluation of the condition at the time of primary healing

The object of the present study then was

(1) to find a more accurate objective method for assessing the *condition at the time of primary healing*

For this purpose there can be no question of anything but *ra*

diological assessment, as clinical assessment cannot afford a sufficiently differentiated and objectively reliable evaluation

(2) if possible to find a *correlation* between the *radiological appearances at the time of primary healing* and the *late clinical symptoms*, so that at this early stage it is possible to assess the risk of osteoarthritis in a given series

It is this last mentioned item which is the most important one from a practical clinical point of view—and in fact the main object of the present study. At the same time however it is that part of the task which is most difficult—and at present perhaps impossible—to solve.

The presupposition of its solution is previous knowledge of the *entire* radiological and clinical course of LCPD after some form of treatment from the time that the diagnosis was made throughout the treatment period until primary healing—and *after that for a minimum of 25 years*. Only thereby is there a chance of getting an idea of which features of the primary radiological appearances determine the subsequent clinical course. This knowledge then may be used for assessing the primary results of *other* therapeutic methods.

Investigations of this nature have been extremely sparse. The two most detailed ones are by Helbo and Sundt.

Helbo has reported a follow up examination of 52 patients at least 25 years after the onset of LCPD. These patients were either *untreated or had received only symptomatic treatment*.

Out of the 52 patients 5 have to be left out as they are unsuited for the investigation.

Among the remaining 47 the radiological status at the time of primary healing was as follows:

5 had healed showing "spherical head"
29 had healed showing "greatly flattened head"
13 had healed showing "irregular angular head"

These radiological characteristics represented the result of a mere estimate.

At follow up it was found that *no* patient with spherical and *all* patients with "irregular" heads had developed osteoarthritis. Out of the 29 patients with greatly flattened heads 19 (66 per cent) developed osteoarthritis while 10 did not.

Helbo concluded that the *radiological shape of the head* at the time of primary healing played a decisive role in the development of secon

dary osteoarthritis Slight deformity did not lead to osteoarthritis while in the event of greater deformity the risk is considerable—increasing with the severity of the deformity Of course the *wear on the joint* is a factor too but according to Helbo s studies of less importance than the deformity

Sundt had an appreciably larger series viz 153 patients (172 hip joints) The majority of his patients too were in fact untreated He after examined 137 patients – 153 hip joints 69 joints more than 25 years after the onset of the disease

At an estimate he divided these hip joints into 4 groups according to the shape of the head at the time of primary healing (1) spherical (2) ovoid (3) cylindrical (4) quadrangular

The radiological status of the 69 after examined hip joints at the time of primary healing had been

(1) spherical head	6 hip joints
(2) ovoid heads	25 hip joints
(3) cylindrical heads	36 hip joints
(4) quadrangular heads	2 hip joints

At follow up *none* of the best group and all of the poorest group had osteoarthritis Out of the second group (ovoid) 48 per cent (12/25) and out of the 3rd group (cylindrical) 72 per cent (26/36) had osteoarthritis This result corresponds in all essentials to Helbo s

These two studies may then be briefly summed up as follows

The number of patients after examined 25 years after the onset of the disease is quite large—about 100 patients However the radiological description of the status at the time of primary healing proved to be *based merely on an estimate* in both series without any attempt at a more accurate assessment Therefore on the face of it it would not seem possible to use these two studies as a basis for a more detailed description of the relation between the radiological appearances at the time of primary healing and the risk of osteoarthritis

This is not saying that the studies concerned are of no interest—on the contrary

Both authors arrived at the same general conclusion

The more the hip joint—in this case the head of the femur—differs from the normal shape the greater is the risk of osteoarthritis

This may sound like a platitude but in fact it is the general basis for all radiological assessments in the present study—and therefore seems to be worth stressing

However such a general basis for assessment is of little assistance when the intention is to predict in a given series at the time of primary healing which patients—and how many—are going to develop osteoarthritis at a later date

But if we have *two* series treated by different methods and if we are able to *measure* the deformity of the hip joint with accuracy it is possible to form on the basis of the dictum the greater the deformity the greater the risk of osteoarthritis an estimate of the *relative* risk of osteoarthritis in the two series i e to establish which of the two therapeutic methods is more effective—and possibly to obtain a measure of the difference

Maybe it is also possible by a more detailed mapping of individual series—at the time of primary healing as well as after a long follow up period—to arrive at a prognostic assessment in a single case material

Our first object then is to arrive at relevant well defined radiological criteria as to how much a joint which has been affected by LCPD differs from the normal *shape* of the hip joint

But before dealing with the X ray appearances under normal and pathological conditions it seems reasonable to recapitulate the *anatomical* characteristics of the normal hip joint

NOTES ON THE NORMAL ANATOMY OF THE HIP JOINT

The hip joint connects the femur with the pelvis and is a *ball and socket joint*

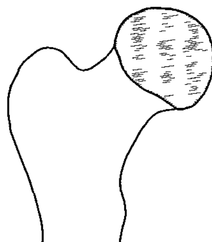
The *joint surface of the femur* in adults makes up 2/3–3/4 of a spherical surface

That part of the femur which is covered by the joint surface is called the head of the femur

In adults down to the age of 14–16 years the head of the femur consists exclusively of bony tissue In children from the age of 14–16 and downwards the head consists partially of cartilage—the younger the individual the more the cartilage

The head is formed by two parts the *epiphysis* and the diaphyseal part of the head called the *metaphysis* These two components are separated by the epiphyseal line (epiphyseal plate) or—in adults—by its traces in the osseous structure The demarcation of the head from the neck on the surface of the femur is the edge of the joint surface which does *not* form a circle at the junction to the neck but a slightly

ANTERIOR VIEW



POSTERIOR VIEW

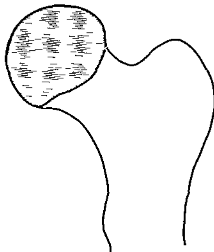
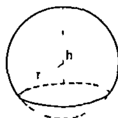


Figure 1 A normal femoral head The edge of the joint surface is undulating

SPHERICAL SEGMENT



HEAD OF FEMUR

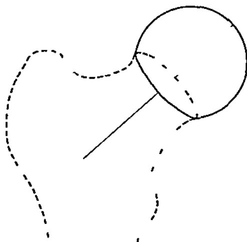


Figure 2 The head of the femur may be described as a spherical segment

undulating line which extends most distally on the anterior and posterior aspects of the neck while medially and laterally it is more proximal (Figure 1) However the undulating line which demarcates the joint surface does not differ much from a circle The head may therefore be described as a spherical segment—*i e* a body delimited

However such a general basis for assessment is of little assistance when the intention is to predict in a given series at the time of primary healing which patients—and how many—are going to develop osteoarthritis at a later date

But if we have *two* series treated by different methods and if we are able to *measure* the deformity of the hip joint with accuracy it is possible to form on the basis of the dictum the greater the deformity the greater the risk of osteoarthritis an estimate of the *relative* risk of osteoarthritis in the two series *i e* to establish which of the two therapeutic methods is more effective—and possibly to obtain a measure of the difference

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In adults down to the age of 14–16 years the head of the femur consists exclusively of bony tissue In children from the age of 14–16 and downwards the head consists partially of cartilage—the younger the individual the more the cartilage

The head is formed by two parts the *epiphysis* and the diaphyseal part of the head called the *metaphysis* These two components are separated by the epiphyseal line (epiphyseal plate) or—in adults—by its traces in the osseous structure The demarcation of the head from the neck on the surface of the femur is the edge of the joint surface which does *not* form a circle at the junction to the neck but a slightly

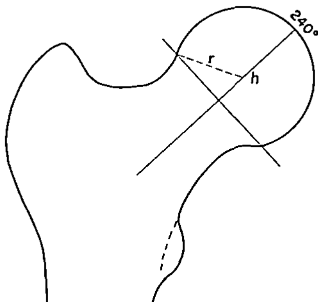




Figure 3 On the X ray film the normal femoral head is demarcated by
(1) a circular arc of about 240
(2) a line through the end p ints of the circular arc
the baseline (9 7/12 ♂ 14 2/12 ♂)

ing shape of the edge of the articular surface this gives the best possible impression of the demarcation of the femoral head—and thereby of the articular surface (Figure 4) In comparing the diseased and the sound side the most important factor is that the baseline be passed through the same points on both sides

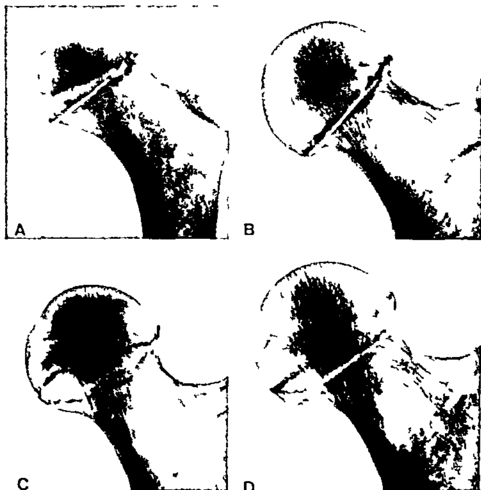


Figure 4 Edge of joint surface and baseline X ray film of bones on which the edge of the joint surface of the femoral head is marked by a contrasting paint The baseline is drawn on the X ray film as stated in the text (1 child (A) 3 adults) The baseline cannot be traced with as much accuracy in adults as in children since in adults the epiphyseal line is visible only as an indistinct trace in the bone As a rule it is drawn too far distally (d) because during puberty the edges of the epiphyses are prolonged distally

Medially the joint surface extends to the level of the bottom limit of the tear drop figure and as a rule the junction of the convex joint surface and the concave contour of the neck is not difficult to trace

Since in the following the baseline will be used in the various measuring methods it is of course very important that it should be *well defined* This demand is fulfilled by the baseline described as

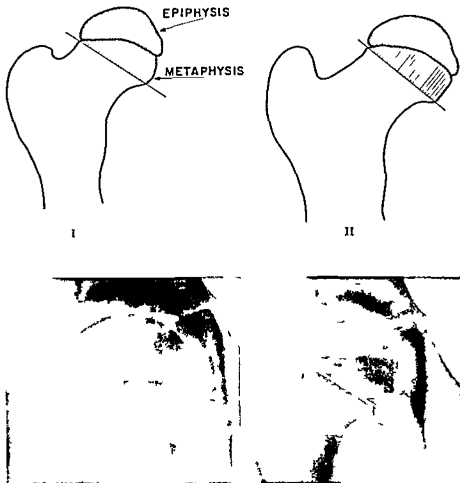


Figure 5 Normal femoral heads Epiphysis and metaphysis
(X ray films ♂ 14 9/12 years ♀ 8 8/12 years)
(I traced from Klein et al Slipped Capital Femoral Epiphysis Springfield U S A 1953 Figure 44 II traced from Lanz & Wachsmuth Praktische Anatomie I Berlin 1938 Figure 116)

far as is possible with a radiologically determined line At any rate it is just as well defined as the epiphyseal line—if anything better that is when the femur is in 20 internal rotation so that the neck is parallel with the film

The *circular arc* which forms the periphery of the head has its centre approximately in the middle of the head—i e at a distance of about 1/3–1/2 radius from the baseline



hip joints Epiphysis and epiphyseal line in various age groups (♀ 5 7/1 and ♀ 8 years)



Figure 7 Normal hip joint
The metaphysis is visible as a rectangle in the lateral view

On the X ray film too the bony head consists of two parts separated by the epiphyseal line the *epiphysis* and the *metaphysis* The line which represents the base of the head is approximately at right angles to the axis of the neck while the base of the epiphysis is more horizontal Therefore the metaphysis stands out like a wedge (triangle) whose base is medially and tip laterally oriented (Figure 5)

However this applies only to age groups in which the epiphyseal line forms a *straight line* viz from approx 5 to 12 years of age

Above the age of 12 the epiphyseal line manifests itself as an upward convex line the edges of the epiphysis bending down in a tip laterally as well as medially Medially this tip may completely cover the medial surface of the metaphysis so that above this age the epiphysis may form the only base for the articular cartilage

Below the age of 5–6 years the epiphyseal line is wider—and at the age of 2 years or below no actual epiphyseal line is visualized The small round ossification center is completely separated from the metaphysis by a broad space corresponding to the cartilage in the non ossified part of the femoral head In this age group therefore the epi and metaphysis do not form an entity with an unbroken contour (Figure 6A)

At the age from 3–5 years there will be the beginning of an epiphyseal line but as the outline of the epiphysis is still double convex the epiphyseal line now stands out as a downward convex line The epi

and metaphyseal contour is now more uninterrupted but does not yet make up part of a circle as in the older age groups

All this applies to the anteroposterior view In the lateral view the metaphysis during the age group 5–12 years is a small rectangle just distal to the epiphysis (Figure 7)

The outlines of the normal acetabulum are seen at ages over 5 years as a clear semicircle concentric with the articular surface of the head It is most clear and sharp upwards lateral to the acetabular notch but in its medial part too the contour is quite well traced as a continuation of the circular arc

THE PATHOLOGICAL X RAY APPEARANCES

A description of the pathological X *ray picture* can only be rendered in relation to what is known—or felt to be known—about the *pathological anatomy*

The following description therefore will be given with constant reference to and comparison with the *pathological anatomical course*

LCPD is generally considered as *a disease localized primarily to the capital epiphysis In untreated cases this leads to flattening and widening of the epiphysis The object of treatment is to prevent this process*—but as a rule it is only partially successful

The other changes observed in the hip joint viz changes in the shape of the remaining parts of the head (metaphysis) and of the acetabulum widening of the neck the general increase in growth of bone around the joint merely represent the reaction of the surrounding osseous components to the deformation of the epiphysis

This should not lead anyone to believe that these *secondary changes* consist exclusively in *passive* adaptation to the flattened epiphysis As far as the head is concerned there is certainly a question of compensatory processes striving to remedy the effect of the flat epiphysis *upon the shape of the head making it differ as little as possible from* normal

The acetabulum on the other hand adapts itself more passively to the final result of epiphyseal flattening + the compensatory growth processes in the head so that the joint surfaces acquire the same shape—perhaps concentric—with a joint space of uniform width It is often stated that *subluxation* of the head in the acetabulum is an important sequel of LCPD This subluxation is said to manifest itself in th[illegible] that a larger part of the capital joint surface than normal is

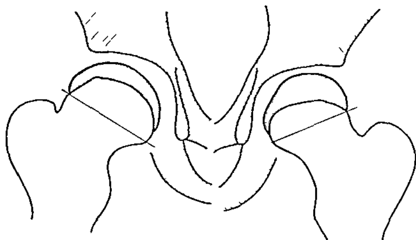




Figure 8 12 year old ♀ Sequelae of right sided LCPD Right capital epiphysis the shape of a new moon

situated outside the lateral edge of the acetabulum However this need *not* be a sign of actual subluxation it may be due merely to a disproportion between an enlarged femoral head and a relatively small acetabulum Subluxation is present only if the joint space is wider medially than laterally This is no uncommon finding *during the course of* LCPD but as a rule it disappears after healing—at any rate if a fairly effective relief from weight bearing has been carried through

In the event of very severe deformities of the head *after* the course

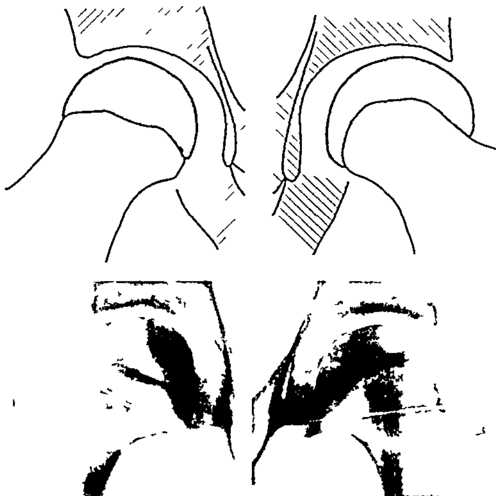


Figure 11 13 year old ♀ Sequelae of left side LCPD. Left capital epiphysis the shape of a new moon caput magnum

assessing the primary result of a treatment—exactly the same conclusion at which Helbo and Sundt arrived on the basis of their studies.

Of course one *may* try to record any changes in the position of the head in the acetabulum and the apparent shortening of the neck. However these phenomena are nearly always combined with severe changes of the head and are therefore of subordinate interest.

But what happens in the head of the femur?

The primary change is flattening and widening of the epiphysis. If this consisted merely in the height of the epiphysis being reduced and its width increased, the remainder of the head adapting itself

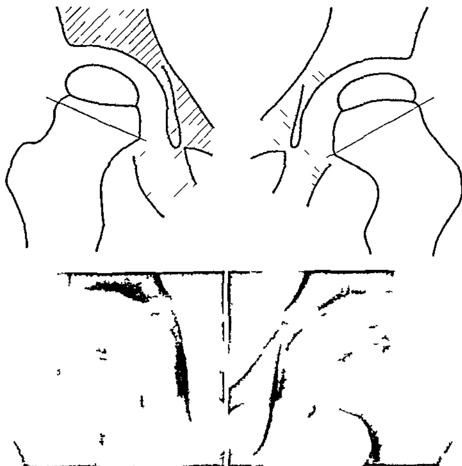


Figure 1? 5 year old ♂ Left sided LCPD Metaphyseal console

accordingly the flattening of the epiphysis would directly determine the shape of the head and measurement of the epiphyseal deformity would afford a direct impression of the shape of the entire head

But as stated above this is not so The epiphysis does not merely become flatter and wide It also curves so that on the X ray film it assumes *the shape of the new moon* with the convexity upward *This counteracts the flattening of the head its circular contour* is preserved still being about 220–240 with its centre at the approximately normal place in the head The metaphysis grows up into the concavity of the new moon i e it grows larger and the epiphyseal line now manifests itself as an upward convex line (Figures 8 9 10)

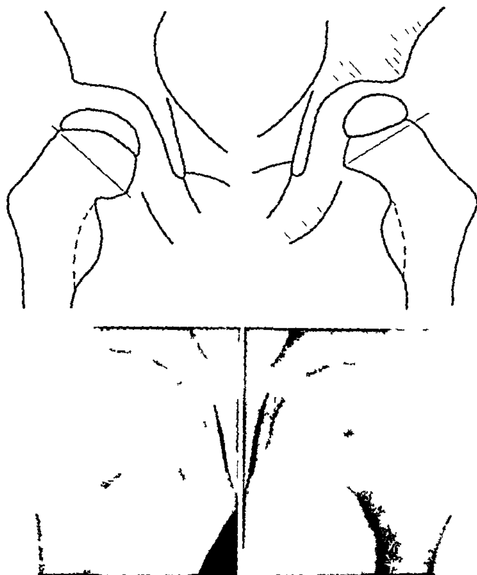


Figure 13 5 year old ♂ Right sided LCPD "Metaphyseal console

If the epiphysis increases *greatly* in width it cannot—despite its curving be contained within the normal contour of the head This would lead to flattening of the head if the head did not acquire a larger surface by *diffuse growth* which gives room for the flat wide curved epiphysis without the head as a whole getting flat and wide (Figure 11)

… or able to interpret the growth of the metaphysis up into

the concave new moon and—at least partially—the diffuse growth of the head as *compensatory reparative* processes which despite the flattening of the epiphysis strive to maintain the normal shape of the head This *may* be completely successful although the epiphysis is visible only as a narrow sickle across the surface of the head In such particularly successful cases the head presents itself as a moderate *caput magnum* of an entirely normal shape

But in such instances a measure which merely represents the flattening of the epiphysis does not by any means give an impression of the shape of the head

This form of compensation for epiphyseal deformity occurs mainly in the higher age groups from 8 years and upwards Another form may be observed in the age range 5–8 years In this age group the epiphysis becomes flatter and *smaller* It does not get appreciably wider and therefore it is more rarely new moon shaped The metaphysis compensates for the small flat epiphysis by increasing in size and forming a large *metaphyseal console* below the small epiphysis (Figures 12 13) This preserves the normal shape of the head which is now made up mainly of the metaphysis The head does not increase appreciably in size unless the epiphysis also widens

In cases having a metaphyseal console measurement of the epiphyseal flattening also gives no impression of the shape of the head

Thus in a considerable number of cases these reactions on the part of those components of the head which are outside the epiphysis can maintain the head in its approximately normal shape

However if the flattening of the epiphysis becomes *too* pronounced things get more difficult

In such cases it is impossible to compensate for the epiphyseal flattening which therefore will affect the shape of the head making it on the whole flatter and wider True the circular contour of the head on the X ray film is preserved but the radius of the circle gets longer and the centre of the circle moves down toward the neck The circular arc no longer makes up 220–240° but approaches a semicircle (180) or gets even smaller when the centre moves down *into* the neck (Figure 14)

If the epiphyseal flattening becomes even more pronounced the circular contour of the head can no longer be maintained The contour gets more curved at the edge and in the case of great flattening quite *irregular* and *angular* (Figure 16)

However it must be pointed out that it is not only the degree of

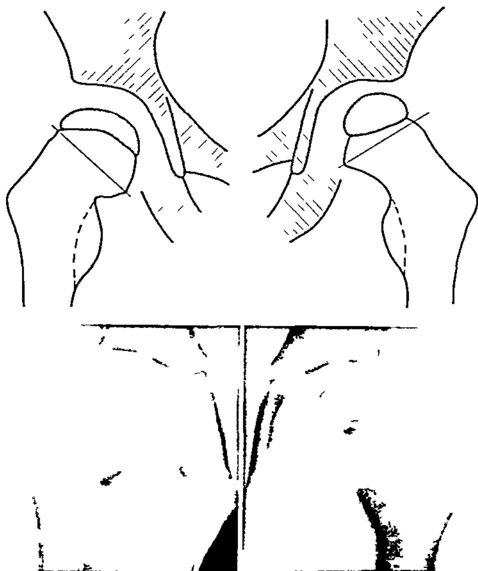


Figure 13 5 year-old ♂ Right sided LCPD Metaphyseal console

If the epiphysis increases *greatly* in width it cannot—despite its curving—be contained within the normal contour of the head This would lead to flattening of the head if the head did not acquire a larger surface by *diffuse growth* which gives room for the flat wide curved epiphysis without the head as a whole getting flat and wide (Figure 11)

It [illegible] [illegible]sonable to interpret the growth of the metaphysis up into

so that even a slight flattening of the epiphysis is accompanied by a corresponding flattening of the entire head

The lacking ability of the metaphysis for growth can only mean that the newformation of bone along the epiphyseal line has ceased or is greatly reduced But this affects not only metaphyseal growth the longitudinal growth of the neck of course ceases too The result is the well known picture of a *wide flat head* on a *short wide neck* (as the *periosteal* transverse growth of the neck does not cease!)

In other words this typical deformity must be interpreted as a sign that in these cases the epiphyseal line has closed at an early stage of the disease This justifies two conclusions

In the first place The worst thing that can be done during the treatment of LCPD is early *drilling* through the neck and epiphyseal cartilage up into the epiphysis This will accelerate the closure of the epiphyseal line and prevent the compensatory osseous processes from exerting their influence—*i e* to preserve the shape of the head despite epiphyseal flattening

In the second place It is not surprising that the therapeutic results in LCPD are the poorer the closer the patient has approached puberty (Mose) In this age group the epiphyseal line is about to close and the epiphyseal cartilage does not possess the growth energy needed for eliciting a brisk compensatory growth of bone The poor results in this age group are not due to greater flattening of the epiphysis but to lacking compensatory osseous growth along the epiphyseal line

Concerning the *factors and processes* active during the course of LCPD which together determine the *radiological* appearances it may then be said

The end result after treatment of LCPD is determined by 2 factors

(1) the epiphyseal flattening
(2) the processes in the remainder of the head which strive to compensate for this flattening

It is the *total effect* of these two factors which determines the shape of the entire head of the femur as seen on the X ray film at the time of primary healing

The flattening of the epiphysis is determined partly by the severity of the disease and partly by the ability of treatment to prevent this flattening, e. g. by relief from weight bearing. In comparing several series of *approximately the same severity*, therefore, the epiphyseal flattening is a *fitting indicator of the therapeutic efficacy*.

As series reported from this country will be of largely the same degree of severity, a method measuring the epiphyseal flattening will afford a good index of the therapeutic efficacy, but not of the prognosis which depends upon the shape of the femoral head.

A method which measures the shape of the entire head, on the other hand, will afford important prognostic data, at least concerning the *relative* prognosis on the basis of the dictum: The greater the deformity of the head, the greater the risk of osteoarthritis.

The shape of the head may be measured in various ways.

First *directly*, *i. e.* so that the result of the measurement directly expresses the shape of the head. To my knowledge no such measurement has been devised.

In the second place measurement of the capital shape may possibly be done by *indirect* methods. Thus *a priori* it cannot be ruled out that a fairly constant fixed relation exists between epiphyseal flattening and the shape of the entire head, so that the results of a method measuring epiphyseal flattening *may* be used as a measure of the shape of the entire head (Mose). However, this does not appear very likely according to what has been stated above. An orientation as to whether such a relation exists at all and—if so—concerning its magnitude may be procured by comparing the results obtained by measuring the epiphysis and the shape of the head in a given series.

If such a relation exists, it must then be investigated whether it exists also in other series and whether in these series it is of the same magnitude.

This is quite an undertaking, and even so one can never be *sure* that such a fixed relation between epiphyseal flattening and capital shape is present in *all* series under *all* circumstances. An indirect measuring method is always uncertain, and a method which directly measures the shape of the head is therefore undoubtedly preferable—if such a method can be devised!

In the fol[illegible]wing the various available—and any new—measuring methods will [illegible] be applied to a given material to ascertain whether

they are applicable in practice and to assess the information obtainable by these methods

Thereafter the result of such a preliminary study is hoped to be applicable for a reliable assessment of the value of *different* therapeutic methods

The material selected for the preliminary study consists of 79 patients with unilateral LCPD treated in the Seaside Hospital Refsnæs during the period 1953–1957 All patients referred to the hospital during this period were included regardless of the treatment they received

The great majority of patients were treated by relief from weight bearing on the affected hip *i e* prolonged bed rest (about 18 months) followed by ambulatory relief from weight bearing *i e* crutches and Snyder s sling for about 6 months (relief from weight bearing for an average of 25 8 months) The assessment was not performed until primary healing had occurred

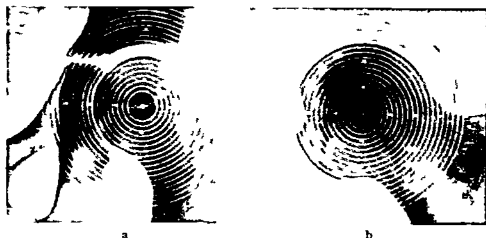
This series is identical with that described in Knud Mose s paper and in the following it will be called the bed rest series unlike other series to be mentioned later treated without bed rest or with traction in bed

This series has now been assessed independently by the author in every detail But let me state that wherever Mose and I have used the same measuring methods and calculations the results differ only negligibly

A more detailed description of this series—its origin definition sex ratio and age distribution etc was given in Mose s thesis In the present paper I shall give only a tabulation of the patients age at the initial symptom and the stage of the disease when treatment was started (Table 1)

From this series it was first endeavoured to pick out a group in which the prognosis could be said to be definitely *poor* The remaining cases then make up a group in which the prognosis is at least *better* than in the first group—in some of the cases even quite good

The grouping was done on the basis of the radiographic findings First the X ray films were arranged—on the basis of a pure estimate—in a long row starting on one side *e g* on the left of the viewer with near normal heads the capital deformity increasing towards the other end (on the right) This row was then divided into 2 groups one in which the articular surface of the affected head after the treatment still made up part of a spherical surface varying from three



a b

Figure 15 Mose's circular plate

quarters of a spherical surface having approximately the same radius as the sound head to a considerably smaller part of a spherical surface with a longer radius—and another group in which the articular surface of the affected head had become irregular and angular

Of course this grouping can be done on the basis of a mere estimate just by viewing the X ray films but a more exact objective method was highly desirable

A transparent plastic plate scored with circles was suggested by Goff as a valuable aid in estimating the shape of the head Now Mose has used a similar plate for a more exact assessment

A transparent plate with a system of concentric circles with a 2 mm difference in radius from 6 to 40 mm is placed on top of the X ray film (Figure 15) If one of the circles is applicable for covering the outline of the head in the anteroposterior view and the same circle covers the outline in the lateral view the head is spherical *i e* its surface is a major or minor part of a spherical surface The plate also gives information regarding the size of the radius of this spherical surface (a 2 mm variation is permitted)

If none of the circles can cover the capital outlines the case is assigned to the other group *i e* that of irregular or angular heads

It may be mentioned that according to Mose's experience—and mine—there are actually no elliptic capital contours As a transition between the definitely spherical and the irregular heads there may be very flat ones the greater part of their surface being nevertheless spherical having a circle-shaped silhouette *i e* a circular arc which is

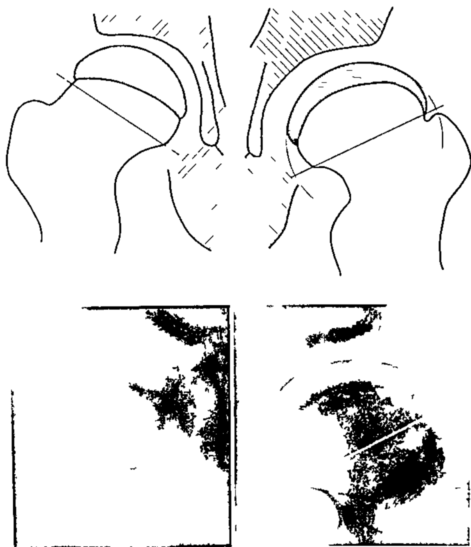


Figure 16 12 year old ♂ Sequelae of LCPD
Transitional variety between spherical and irregular femoral head

small in degrees having a long radius and a centre situated in the neck while the edges have greater curvature and thus a shorter radius (Figure 16)

Such heads should always be classified as irregular but the grouping may be difficult However they occur only in small numbers

It might be imagined also that the grouping into spherical and non

spherical would give rise to difficulties in the young age groups—below 4 years—in which even the normal head does not show an uninterrupted circular contour on the X-ray film. However, this difficulty has never been encountered in practice, as the therapeutic results are never assessed until 3–4 years after the onset of the disease.

On the whole the division into the two groups is very reliable, and Mose's application of Goff's plate means a considerable advance in the evaluation of the therapeutic results in LCPD.

We have now distinguished one group of patients in whom the femoral heads, after the disease has run its course, are so deformed—irregular and angular—that the risk of osteoarthritis must be very great.

The prognosis in the remaining cases—the group with spherical heads—*is more difficult to establish.*

Let us imagine again that the X-ray films for this group are arranged—according to a mere estimate—in a row, starting on the left with the near normal heads, the capital deformity increasing towards the right.

If we view this row, it is evident that the cases on the left have a favourable prognosis, while those on the right have a poorer prognosis—but it is impossible to decide the limit between a good and a poor prognosis by a mere estimate. This requires at least a measuring method which gives an objective measure of the shape of the head.

But even though such measurements were available, it would be impossible—as already mentioned—to decide directly which deformities are going to give rise to osteoarthritis and which not.

However, some guidance is to be had.

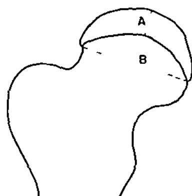
Just as irregular heads indubitably spell a poor prognosis, it may probably be justified to say that when a relevant measuring method shows a head of a shape *within the normal range*, the prognosis ought to be good.

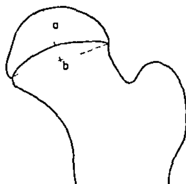
But no such measuring method is available—as yet.

In order to obtain one, it was my object first to try whether, in a given series, a method measuring the *epiphyseal flattening* might perhaps indirectly afford information about the shape of the head. Should this fail, it was intended to try to arrive at a method which *directly* measures the shape of the head.

In the introduction I mentioned a number of the methods used so fa[illegible] the therapeutic results. Measurement of the epiphys

SEQUELAE OF LCPD — NORMAL HIP





EPIPHYSEAL INDEX $\frac{A}{B}$ — EPIPHYSEAL INDEX $\frac{a}{b}$

EPIPHYSEAL QUOTIENT

$$\frac{A \quad b}{B \quad a}$$

Figure 17 Calculation of epiphyseal quotient

eal index (Sjövall) epiphyseal quotient (Eyre Brook) Herndon & Heymann's comprehensive quotient and Jonsäter's caput index

Measurement of the epiphyseal quotient is the method which gives the most reliable information about epiphyseal flattening—and which is based upon the most well defined measurements Furthermore Mose has once measured the epiphyseal quotient in the present material and repeated measurement—carried out independently by another investigator—will if the results show agreement be a weighty argument in favour of the accuracy and reliability of the method

The epiphyseal quotient is found by first dividing on the affected side the greatest height of the epiphysis by its width at the epiphyseal line This gives the epiphyseal index of the affected side This index is then divided by the epiphyseal index on the sound side multiplied by 100 which gives the epiphyseal quotient (Figure 17)

When the epiphyseal quotients are calculated in a series of normal hips (of the same age distribution as the present series) the values generally range from 90–100 while a smaller number are between 85–90 *The normal minimum value must be said to be 85* (the epiphyseal quotients were measured on X rays of 80 normal hips The lower index is the numerator)

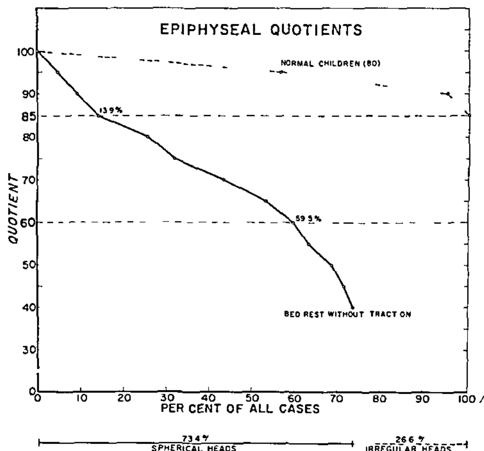


Diagram 1 Epiphyseal quotients *(bed rest without traction Refsnæs 1953 57 79 pts) Epiphyseal quotients plotted along the ordinate The number of patients in per cent plotted according to decreasing epiphyseal quotient along the abscissa That part of the abscissa which is within the right end point of the curve signifies the number of patients with spherical heads (73 4 per cent) that part which is outside this point the number of patients with irregular heads (26 6 per cent) The broken curve indicates the epiphyseal quotients in 80 normal children (Table 41)*

The result of calculating the epiphyseal quotient in the bed rest series may be seen from Diagram I —From this diagram it may be seen that only about 14 per cent of the patients have an epiphyseal quotient exceeding 85—the normal minimum

If the epiphyseal quotient were a direct expression of the shape of the head this would be an extremely poor result!

But it is not The compensatory processes in the head lend far more than 14 per cent of the patients an approximately normal head

This was also realized by Mose Indeed he states that careful inspection of the X ray films showed that *all patients whose epiphyseal quotients exceeded 60 had a normally or near normally shaped head* In other words there was a striking disagreement between the relatively low epiphyseal quotients in the greater part of the series and the large number of well shaped heads

Mose accordingly established the rule that all patients whose epiphyseal quotients exceeded 60 could be defined as a group having such well shaped heads that the result had to be called good

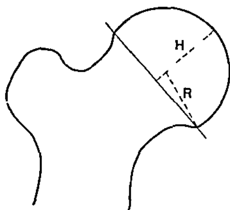
This rule which I shall call *Mose s rule* was thus set up in the attempt at getting an indirect measure of the capital shape by measuring epiphyseal flattening

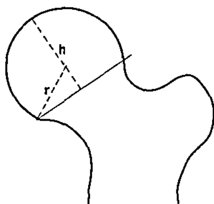
As is apparent from the diagram about 60 per cent of the patients had an epiphyseal quotient exceeding 60

Herndon & Heymann were struck by the same disagreement between the low epiphyseal quotients and the surprisingly well shaped heads But they tried to arrive at a measuring method which is more in agreement with the shape of the head by combining the epiphyseal quotient with another 3 quotients relating to factors which also change in the course of LCPD head neck quotient acetabular quotient and acetabulum head quotient However none of these 3 quotients proved to alter materially during the course of the disease or at least far less than the epiphyseal quotient Obviously when an average of the epiphyseal quotient and 3 near normal quotients is calculated the values found will be closer to normal than the epiphyseal quotients alone and therefore in better agreement with the relatively large number of well shaped heads

Herndon & Heymann also found that 60 per cent of the patients treated (for a relatively short period) with bed rest and traction followed by ambulatory non weight bearing had a comprehensive quotient exceeding 80 corresponding to a result which at an estimate must be called excellent and good Evidently they feel that now there is a reasonable agreement between measuring method and estimate

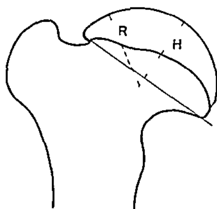
It is not clear why it is better to use a comprehensive quotient and a limit of 80 than the epiphyseal quotient alone and a limit of 60 There is nothing to indicate that Herndon & Heymann s other 3 quotients include particularly the shape of the head in the measuring method The comprehensive quotient is in all essentials merely a fortuitous numerical reduction of the epiphyseal quotient





SEQUELAE OF LCPD

NORMAL HIP





JOINT SURFACE INDEX

$$\frac{H}{2R}$$

JOINT SURFACE INDEX

$$\frac{h}{2r}$$

JOINT SURFACE QUOTIENT

$$\frac{H\ r}{R\ h}$$

RADIUS QUOTIENT

$$\frac{R}{r}$$

Figure 18 Calculation of joint surface quotient *and* radius quotient

In brief Moses's as well as Herndon & Heymann's assessment of which heads—and thereby joints—may be called good etc is based exclusively upon simple direct inspection of X ray films and is thus in fact a mere estimate

Others have used different estimates Katz for instance states that the epiphyseal quotients must exceed 75 for the result to be called good (Katz satisfactory) while Moses's good group goes right down to an epiphyseal quotient of 60 Possibly both these figures are correct—or reasonable—for *the respective series* but it is possible also that the difference is due merely to different personal estimates as to what is considered good This shows however that the epiphyseal quotient is a frail basis for assessing the shape of the head—and thereby the prognosis On the other hand nobody will deny that it is an excellent measure of the ability of treatment to prevent epiphyseal flattening

It is necessary therefore to arrive at a method which gives a more direct measure of the shape of the head

The head is defined as that part of the femur which is covered by the joint surface The shape of the head therefore is determined by the shape of the joint surface

Normally the joint surface is shaped as 2 3–3 4 of a spherical surface demarcated from the surface of the neck by a slightly undulating line which however without major error may be described as a circle In other words the head may be considered a spherical segment and the joint surface as its curved surface The area of the joint surface expressed as a fraction of a whole spherical surface having the same radius is then $\frac{2\pi r h}{4\pi r^2} = \frac{h}{2r}$ in which h is the height of the spherical segment and r the radius of the spherical surface This quantity is called the *joint surface index* h and r—and thus also the joint surface index—may be measured on the X ray film (Figure 18)

During the course of a LCPD the head as a whole becomes deformed—flattened In cases where the joint surface preserves its character as a spherical surface it will—when measured as a fraction of a whole spherical surface—be diminished *i e* the joint surface index decreases with increasing flattening In these cases the joint surface index affords a well defined measure of the shape of the entire head 3 4 sphere 1/2 sphere etc *i e* a spherical segment whose surface is 3 4–1/2 of a whole spherical surface

The joint surface index on the diseased side may be compared with that on the unaffected side by dividing the former by the latter. This gives the *joint surface quotient* $\frac{H \times r}{R \times h}$ in which the capital letters indicate the measurements on the diseased side and the small letters *the measurements on the sound side. This quotient is an accurate* objective measure of the alteration in the shape of the head during the course of LCPD. It is stated multiplied by 100 and in 80 normal children it ranged from 100–85.

The shortcoming of the joint surface index and joint surface quotient is that these quantities remain entirely unchanged when H and R increase proportionally, *i.e.* when the head increases in size without changing in shape or in other words when it develops into a "caput magnum"—which *may* be the only sequel of LCPD.

On the other hand, such an increase in capital size affects the radius of the head—which will of course become longer than on the sound side.

However, the length of the radius is not influenced only by a pure increase in growth. When during an LCPD the head preserves its spherical shape but gets flatter, the centre of the joint surface will move down towards, possibly into the neck. That is, the length of the radius will *also* be increased by flattening of the head.

This is important because it makes it possible to employ the length of the radius for a more accurate assessment of the therapeutic results. The fact is that the flattening of the head is usually accompanied by a very considerable increase in growth.

Just as the joint surface quotient may be calculated from the joint surface index, it is possible to calculate a *radius quotient* by dividing the radius of the diseased side by that of the unaffected side—and multiply by 100. In 80 normal children this quotient ranged from 100 to 115 (Figure 18).

If this radius quotient is used for assessing a therapeutic result it records the flattening *as well* as the increase in the size of the head while the joint surface quotient records only the flattening. It is therefore not surprising that as a rule the radius quotient usually records a greater difference from normal than the joint surface quotient (cf. Appendix II).

Since, however, the increase in growth is presumably not of as much prognostic importance as the flattening, the radius quotient will probably be too pessimistic a prognostic indicator. As one cannot

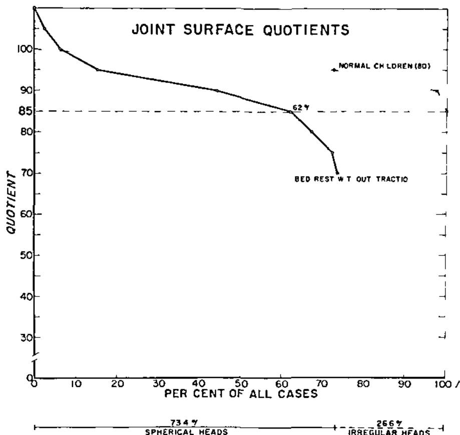


Diagram ? Joint surfa e quotients (bed rest without traction Refsnæs 1953–57 79 patients) Joint surfac quotients plotted along the ordinate The number of patients in per cent plotted according to decreasing joint surface quotient along the abscissa That part of the abscissa which is within the right end point of the curve signifies the number of patients with spherical heads (73 4 per cent) and that part which is outside this point the number of patients with irregular heads (?6 6 per cent) The broken curve indicates the joint surface quotients in 80 normal children (Table 4)

entirely disregard the increase in growth the joint surface quotient is possibly too optimistic

All considered however the joint surface quotient will probably be a better prognostic guide

After these more theroretical considerations the two suggestions for new measuring methods will be tested in practice and their results compared with those found by measuring the epiphyseal quotient

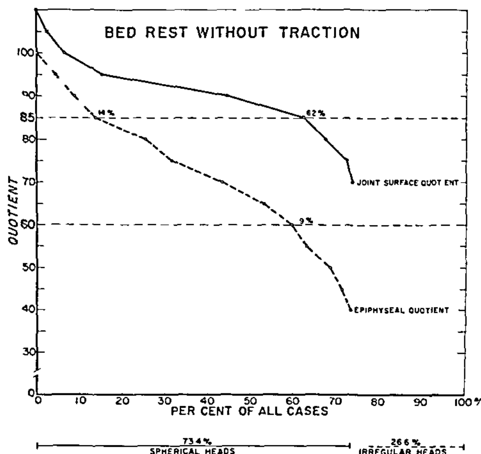


Diagram 3 Epiphyseal quotients *and* joint surface quotients *(bed rest without traction Refsnæs 1953-57 79 pts.) See legends to Diagrams 1 and 2 (Table 41)*

Diagram 2 shows the *joint surface quotients* of the material plotted in the same way as the epiphyseal quotients in Diagram 1

The curve will be seen to differ greatly from that in Diagram 1 62 per cent of the patients have joint surface quotients exceeding the normal minimum (which is 85 also for the joint surface quotient) while only 14 per cent of the patients have epiphyseal quotients above this limit (Diagram 3)

It will be noticed that the highest joint surface quotients are *in excess of 100* This is because in certain rather mild cases of caput magnum without flattening a slight increase in the joint surface index will occur on the affected side as the head has evidently in

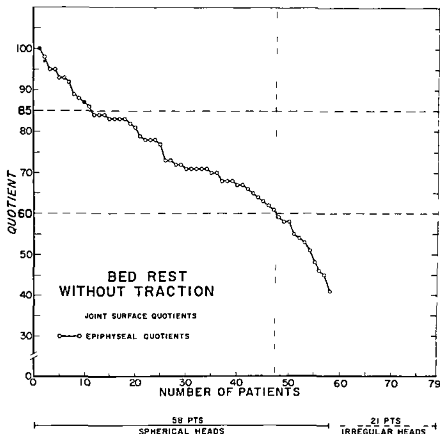


Diagram 4 Epiphyseal quotients *and* joint surface quotients *(bed rest without traction Refsnæs 1953–57 79 patients) The patients are plotted singly along the abscissa according to decreasing epiphyseal quotient Epiphyseal quotients and joint surface quotients plotted along the ordinate For each patient a circle for the epiphyseal quotient and a dot for the joint surface quotient (Table 41)*

creased in size in relation to the width of the neck and the joint surface accordingly makes up a larger part of a spherical surface than on the sound side

Mose s radiological estimate viz that 60 per cent of the patients have a normally or near normally shaped head then appears to have been confirmed by a purely objective measurement of joint surface quotients This agreement may of course also be taken as a confirmation that the joint surface quotient is not only theoretically but also in reality a measure of the shape of the head

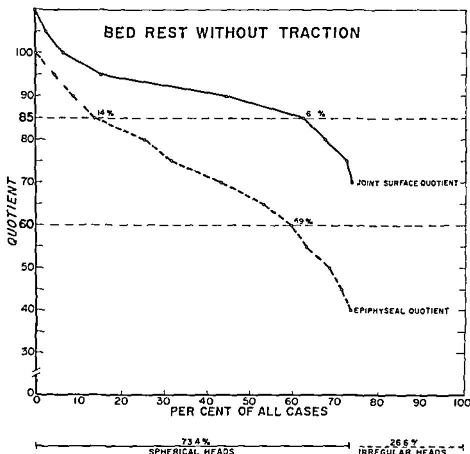


Diagram 3 Epiphyseal quotients *and* joint surface quotients *(bed rest without traction Refsnæs 1953–57 79 pts.) See legends to Diagrams 1 and 2 (Table [illegible])*

Diagram 2 shows the *joint surface quotients* of the material plotted in the same way as the epiphyseal quotients in Diagram 1

The curve will be seen to differ greatly from that in Diagram 1 62 per cent of the patients have joint surface quotients exceeding the normal minimum (which is 85 also for the joint surface quotient) while only 14 per cent of the patients have epiphyseal quotients above this limit (Diagram 3)

It will be noticed that the highest joint surface quotients are in excess of 100 This is because in certain rather mild cases of caput magnum without flattening a slight increase in the joint surface [illegible] will occur on the affected side as the head has evidently in

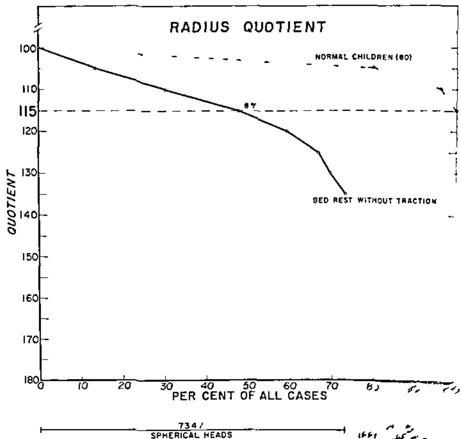


Diagram 5 Radius quotients *(bed rest with ut traction R fa we j r Radius quotients plotted along the ordinate The numl er f j tie plotte l according to increasing radius quotient along th abs l e abscissa which is within the right end point of the curv al e patients with spherical hea ls (73 4 per cent) and the j rt number of patients with irregular heads (26 6 per cent) Th the joint surface quotients in a number of normal ch ll*

head This can be obtained only by measuring th tient which is a direct measure of the shape of t out those patients whose joint surface quotient range i e above 85

The epiphyseal quotient only expresses th physis As this is determined to a marked exte relief from weight bearing the epiphyseal

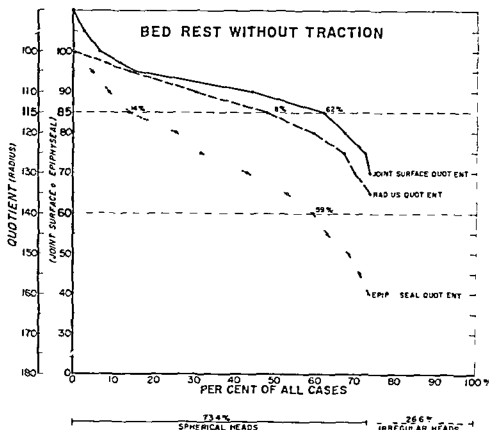


Diagram 6 Epiphyseal quotients joint surface quotients and radius quotients in patients treated with bed rest without traction Refsnæs 1953-57 (79 patients) Cf also legends to Diagrams 1 2 and 5 (Table 41 - 3)

measure of the extent to which the treatment has been able to prevent epiphyseal flattening

In brief Measurement of the joint surface quotient and of the epiphyseal quotient afford different but in both cases valuable information the joint surface quotient regarding the *prognosis* and the epiphyseal quotient regarding the *direct effect of the treatment upon the epiphyseal shape*

Diagram 5 is a graphic representation of the *radius quotients* in the bed rest series—analogous with the representation of the epiphyseal quotients and joint surface quotients in Diagrams 1 and 2 (Diagram 6)

By this measuring method *only 48 per cent* of the patients were found to have radius quotiens below the normal maximum (115)

This value—48 per cent—is lower than found by measuring the joint surface quotients (62 per cent)—and is not in keeping with Mose s radiological estimate of the size of the group called good (60 per cent) This is a natural consequence of the influence upon the radius quotient of the flattening *as well as* increase in size of the head while the joint surface quotient is influenced only by the flattening Accordingly measurement of the radius quotient is a stricter assessment of the therapeutic results and gives a lower proportion of successful cases (Appendix II)

In a radiological estimate the viewer is bound to attach most importance to those changes in the shape of the head which are due to flattening while the increase in its size is less striking Therefore the radiological estimate will very naturally be in better agreement with the joint surface quotients

The question is then ultimately whether the radius quotient or the joint surface quotient is a more reliable *prognostic* guide As far as I can see it is more likely that the changes of the head due to flattening must be prognostically more important and that the increase in size must be subordinate—int *al* perhaps because it is compensated for during the patient s further growth If this holds true *measurement of the joint surface quotient gives the most reliable prognostic information* This again means that about 60 per cent of the patients in the bed rest series—in agreement with Mose s radiological estimate—ought to have a favourable prognosis As already pointed out however this cannot be decided with certainty until there has been occasion to measure the joint surface quotient and the radius quotient in a group of patients treated for LCPD and then evaluate the clinical and radiological result at least 25 years later

Such an investigation has not yet been carried out

The total result of this section on measuring methods is then

A grouping into cases with spherical and cases with irregular femoral heads is the necessary basis for any assessment of therapeutic results This grouping sorts off the cases which have a poor prognosis—*i e* those which have healed with irregular heads Thereafter the remaining cases *i e* the group of cases with spherical heads may be further assessed by measuring the epiphyseal quotient the joint surface quotient and the radius quotient

The epiphyseal quotient is neither a direct nor an indirect measure

of capital shape—but of epiphyseal shape The joint surface quotient on the other hand is a direct measure of the shape of the head the radius quotient of its shape and size

As it is the shape of the head which decides the prognosis measurement of the joint surface quotient affords the best prognostic guidance

In the present material there was agreement between the number of good results measured by the epiphyseal quotient and by the joint surface quotient—approx 60 per cent by both methods However this agreement is only apparent The value does not represent the same 60 per cent of the patients—and the selection resulting from the measurement of the joint surface quotient corresponded best to the term good results as the joint surface quotient is the most reliable prognostic guide

This is not saying that measurement of the epiphyseal quotient is devoid of interest On the contrary This quantity may be considered an excellent—and sensitive—indicator of the effect of treatment upon the capital epiphysis

Radiological Evaluation of the Various Forms of Treatment

This assessment was done on three groups of patients treated for unilateral LCPD One with *traction in bed* one with *bed rest without traction* and one with *ambulatory relief from weight bearing*

According to the conclusion drawn in the last chapter any assessment of the therapeutic results ought to include as far as possible all three measures *epiphyseal quotient joint surface quotient* and *radius quotient* Each measures well defined—but mutually different—properties of the femoral head so that the use of all three methods gives the most varied and detailed picture of the results Any case healed with a spherical head may in fact be characterized by *3 figures* viz the results of the 3 above mentioned measuring methods Example The case illustrated in Figure 8 58-92 109

However this ideal can only be attained in the two first mentioned series not in the third This is a series of patients with unilateral LCPD treated with ambulatory relief from weight bearing and *reported by Mose* The treatment consisted mainly in ambulatory relief from weight bearing by using a Thomas brace crutches and elevation of the opposite shoe for 17–26 months average 2? 2 months *Any mention below of ambulatory treatment refers exclusively to this form of ambulatory treatment* when nothing else is stated Mose measured the epiphyseal quotients in this series but I did *not* have occasion to measure the joint surface and radius quotients Since it is important to compare the results obtained by ambulatory relief from weight bearing with those of the other two forms of treatment and since Mose s and my measurements of the epiphyseal quotient have proved to agree I felt that it was reasonable to include this series in the study and to compare it with the other two as far as Mose s data permit

However the central point of the study is of course the comparison between those two series in which all 3 measuring methods can be applied

Thus the three series which form the basis of the present study were this *ambulatory* series described in Mose s thesis the series treated

with *prolonged bed rest*, and lastly a series of patients treated in the Seaside Hospital Refsnæs with *traction in bed*

This traction series comprises 71 patients with unilateral LCPD treated in the Seaside Hospital Refsnæs from Jan 1 1958 to Jan 1 1962 *All* patients referred to that hospital and treated there for LCPD during these years were included in the analysis regardless of whether or not they were treated with traction (57 patients out of 71 (or 80 per cent) were treated with traction and the others with bed rest alone) Thus we are not dealing with a selected material The treatment was as follows One year of traction in bed followed by about 6 months in bed without traction and thereafter about 6 months of ambulatory relief from weight bearing (crutches and Snyder s sling) The patients were allowed out of bed and on crutches when X ray showed definite signs of incipient newformation of bone around and between the epi physeal fragments

The *traction* was a 1–1½ kg traction on both legs applied for periods of 6 weeks interrupted by two week periods without traction but with close supervision of the condition of the joints in particular the knee joint In other words this was fairly light traction whose main effect has presumably consisted in reducing or abolishing the muscle tonus and securing better immobilization

When the treatment was changed to ambulatory various physio therapeutic measures were cautiously instituted to train the muscles and joints

The final X ray films were in practically all cases read at least one year after the completion of treatment In *all* cases the outlines of the femoral head were uninterrupted and well defined

The *age distribution* and the *stage* of the disease when the treatment was started in all three series are listed in Tables 2 and 3

These tables show that the traction series included a somewhat larger number of children under 4 years of age than the bed rest series If the limit is set at 3 years there is no difference On the other hand the patients treated with bed rest alone arrived for treatment at an earlier stage of their disease

The cases who had ambulatory treatment are more favourable in both respects with a view to obtaining a good therapeutic result

By way of introduction Diagram 7 gives the results obtained by measuring the epiphyseal quotients in the 3 series It is supplemented by the more simplified Diagrams 8 and 9

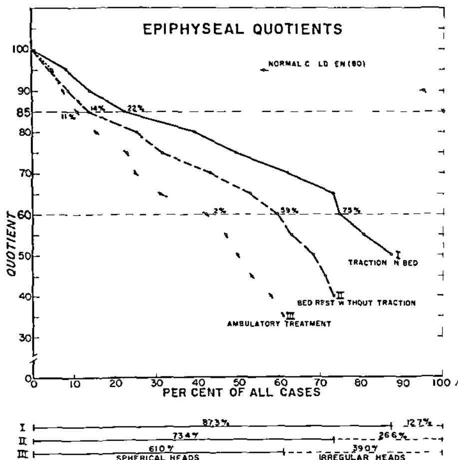


Diagram 7 Epiphyseal quotients in 3 series treated for LCPD by 3 different methods

I Traction in bed Refsnæs 1958–6[illegible] 71 patients

II Bed rest without traction Refsnæs 1953–57 79 patients

III Ambulatory treatment (Mose) 64 patients

The epiphyseal quotients are plotted along the ordinate. The number of patients, in per cent, plotted according to decreasing epiphyseal quotient, along the abscissa. That part of the abscissa which is within the right end point of the curve signifies the number of patients with spherical heads (87, 73 and 61 per cent), that part which is outside this point the number of patients with irregular heads (13, 27 and 39 per cent) (Tables 51, 41, 6)

In the following, the 3 series will be called the "traction series", the bed rest series, and the ambulatory series.

Curve III on Diagram 7 is based, as already mentioned, on Moses measurements. However the ambulatory series includes 7 cases in

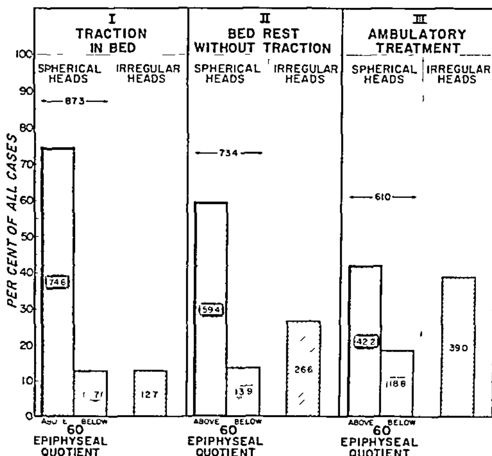


Diagram 8 Distribution of patients with spherical heads and with non spherical (irregular) heads in series I II and III and distribution of epiphyseal quotients above and below 60 in patients with spherical heads

I Traction in bed Refsnæs 1958 (? 71 patients
II Bed rest without traction Refsnæs 1953–5? 9 patients
III Ambulatory treatment (Mose) 6? patients
(Tables 51 ...)

which the epiphyseal quotient could not be measured because there had been LCPD in the contralateral hip Therefore these 7 patients were excluded and the series then is reduced from 71 to 64 patients

The figures plotted on Diagram 7 on a level with epiphyseal quotient 60 represent the number of good results obtained by the application of Mose's rule

It is apparent that 75 per cent of the patients in the traction series had an epiphyseal quotient exceeding 60 This also applies to 59 per

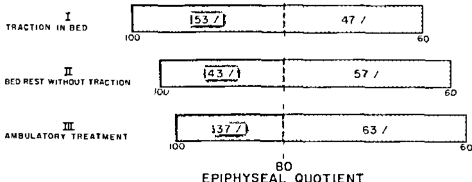


Diagram 9 Distribution of epiphyseal quotients above and below 80 among epiphyseal quotients above 60 in series I II and III

I Traction in bed Refsnæs 1958–[illegible] 71 patients

II Bed rest without traction Refsnæs 1953–57 79 patients

III Ambulatory treatment (Mose) 64 patients

(Tables 51 41 C)

cent of the patients in the bed rest series and 42 per cent of those in the ambulatory series If the bottom limit for good cases is not set at epiphyseal quotient 60 but at 80 (the normal minimum) these figures are 22 per cent 14 per cent and 11 per cent respectively

According to these figures the epiphyseal flattening is considerably less marked in the traction series than in the bed rest series and very considerably less marked than in the ambulatory series This applies not only quantitatively but also qualitatively—as is clearly evident from Diagram 9 (distribution of epiphyseal quotients exceeding 60)

As the major or minor flattening of the epiphysis may be taken to express the efficacy of treatment the figures signify that traction is more effective than the other two methods in preventing epiphyseal flattening

Now the epiphyseal quotients have been measured in 3 series treated by 3 different methods It would be of great interest also to measure the epiphyseal quotients in a series in which the patients had received *no treatment* or only *symptomatic treatment* which according to Helbo does not give better results than no treatment

However a series of this nature is not available to me but Helbo has reported one of 70 patients in which he measured the epiphyseal quotients

The main difficulty of comparing these materials is that Helbo s

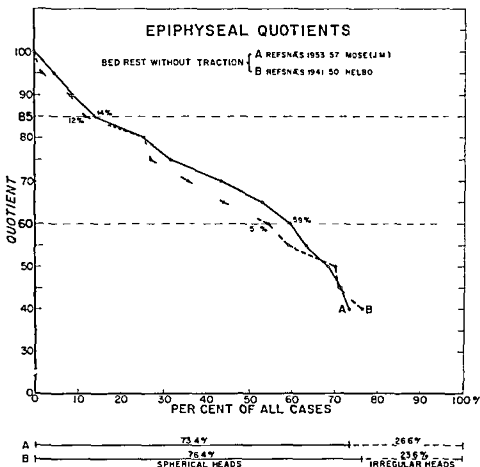


Diagram 10. Epiphyseal quotients in 2 series treated by prolonged bed rest without traction.
A. Refsnæs 1953–57, 79 patients. B. Refsnæs 1941–50, 59 patients.
Epiphyseal quotients in A measured by J. M. Epiphyseal quotients in B measured by Helbo. Cf. also legends to Diagram 1. (Tables 41, 7)

cannot be divided into patients with spherical and non-spherical heads in the sense used by Mose. Helbo divided his patients into 3 groups according to the capital shape: spherical, greatly flattened and irregular, but it is impossible to see whether these 3 groups correspond to Mose's good, fair and poor groups.

Another difficulty is that of course it is impossible to know directly whether Helbo measured his epiphyseal quotients in the same way as Mose and I did in the present 3 series.

Accordingly, the difficulties of comparing Helbo's patients who

received no or only symptomatic treatment with our 3 series would appear to be insurmountable

However there is a way out Helbo has also reported on a relatively large series *i e* 59 patients treated in Refsnaes for unilateral LCPD with prolonged bed rest during the period 1941–1950 He divided the patients of this series into the same groups as the untreated patients (patients with spherical greatly flattened and irregular heads) and measured the epiphyseal quotients

When presupposing *a priori* that Helbo s concept spherical is identical with Mose s spherical head and that his epiphyseal quotients were measured as in our series it would be expected that a curve drawn on the basis of Helbo s epiphyseal quotients in his bed rest series would very closely cover that representing our bed rest series (Diagram 1) It might perhaps be expected to be a little lower partly because the bed rest in Helbo s material was not quite as prolonged as in ours and partly because the number of children under 4 years of age—among whom the most favourable results are obtained—is smaller in Helbo s series than in ours (14 per cent as compared with 25 per cent)

A look at Diagram 10 and Tables 4 and 7 shows that these expectations are fully confirmed—even strikingly so

Although there *may be* some question of chance we may conclude with fair certainty that *Helbo s concept spherical is in all essentials identical with Mose s* and that his epiphyseal quotients were measured as in our series

Now it is permissible to compare our three series with Helbo s patients who received symptomatic or no treatment

The results are shown in Diagram 11 on which the curve representing Helbo s patients treated with bed rest is plotted as well and in Table 8 (age and stage of disease at institution of treatment cf Tables 9 and 10) It is apparent that the results are extremely poor when the patients receive only symptomatic or no treatment also when compared with patients treated by ambulatory relief from weight bearing Spherical heads were found in only 19 per cent of untreated patients while they were found in 61 per cent of those treated with ambulatory relief from weight bearing and in 73 per cent of those treated with bed rest

This result is so bad that it cannot but make one sceptical But when comparing *e g* with Sundt s results we find that in his total series he had only 8 per cent which he designated as spherical This figure corresponds quite well to the number of cases in Helbo s series with

EPIPHYSEAL QUOTIENTS

QUOTIENT

NORMAL CHILDREN (80)

I TRACTION IN BED

II A, II B BED REST WITHOUT TRACTION

III AMBULATORY TREATMENT

IV SYMPTOMATIC OR NO TREATMENT

PER CENT OF ALL CASES

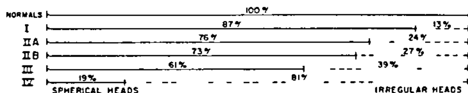


Diagram 11. Epiphyseal quotients in 5 series treated by 4 different methods.
I. Traction in bed. Refsnæs 1958–67. 71 patients, measured by J. M.
II. (A) Bed rest without traction. Refsnæs 1941–50. 53 patients, measured by Helbo.
(B) Bed rest without traction. Refsnæs 1953–57. 79 patients, measured by J. M.
III. Ambulatory treatment. 64 patients, measured by Mose.
IV. No or only symptomatic treatment. 40 patients, measured by Helbo.
(Tables 51, 54, 58)

epiphyseal quotients exceeding 60, i.e. corresponding to Mose's "good" group. When calculating the total number of cases designated as "good" in Mose's list (p. 56 in his thesis) compiled from the literature on results obtained without treatment, we find that they make up only 13 per cent of all treated patients. This is in quite good keeping with the

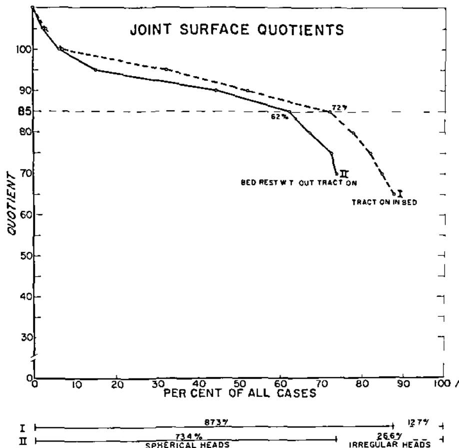


Diagram 1? Joint surface quotients in series I and II
I Traction in bed Refsnæs 1958 C9 71 patients
II Bed rest without traction Refsnæs 1953 57 73 patients
Cf also legend to Diagram ? (Tables 5 4)

number of good results in Helbo s material calculated by the method of Mose i e 8 per cent

A very interesting fact is evident from Diagram 11 as a whole It shows that the *epiphyseal flattening decreases in proportion to the increasing efficacy of non weight bearing*—from symptomatic or no treatment through ambulatory relief from weight bearing bed rest alone to traction in bed —provided that ambulatory treatment affords a less effective relief than bed rest This must be a very strong argument demonstrating that non weight bearing actually does prevent

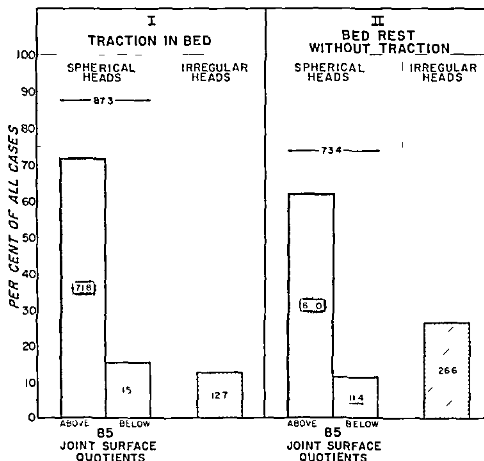


Diagram 13 Survey on patients with spherical and with non spherical (irregular) heads in series I and II and distribution of joint surface quotients *above and below 85 in patients with spherical heads*

I Traction in bed Refsnæs 1958-6? 71 patients

II Bed rest without traction Refsnæs 1953-57 79 patients

(Tables 5 4)*

epiphyseal flattening What previously was a hypothesis has now been confirmed by the analysis of concrete case materials

However although the measurement of epiphyseal quotients may afford an excellent relevant measure of epiphyseal flattening during various forms of treatment it is an unreliable and unsuited basis for assessing the prognosis

To obtain prognostic information we must use methods which ... the *shape of the femoral head* directly As already mentioned

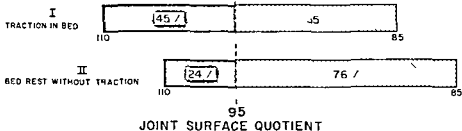


Diagram 14 Distribution of joint surface quotients above and below 95 within the normal range (above 85) in series I and II
I Traction in bed Refsnæs 1958–62 71 patients
II Bed rest without traction Refsnæs 1953–57 79 patients (Tables 5 4)

RADIUS QUOTIENTS

QUOTIENT

100
110
115
120
130
140
150
160
170
180

62%
8%
II BED REST WITHOUT TRACTION
I TRACTION IN BED

0 10 20 30 40 50 60 70 80 90 100%
PER CENT OF ALL CASES

I 87.3% 12.7%
II 73.4% 26.6%
SPHERICAL HEADS IRREGULAR HEADS

Diagram 15 Radius quotients in series I and II
I Traction in bed Refsnæs 1958–62 71 patients
II Bed rest without traction Refsnæs 1953–57 79 patients
Cf also legends to Diagram 5 (Tables 53 43)

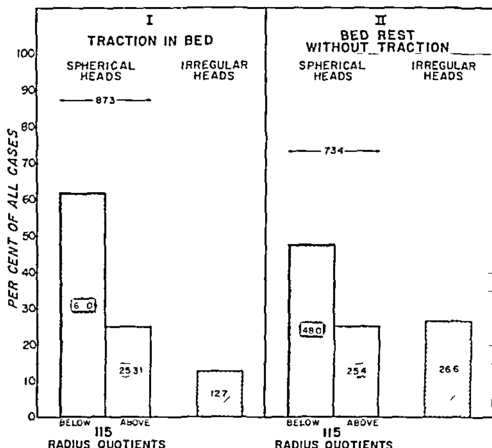


Diagram 16 Distribution of patients with spherical and with non spherical heads in series I and II and distribution of radius quotients *above and below* 115 *among the patients with spherical heads*

I Traction in bed Refsnæs 1958 [illegible] 71 patients

II Bed rest without traction Refsnæs 1958 57 [illegible] patients

(Tables 53 43)

such methods are available i e measurement of the joint surface quotient and of the radius quotient

Diagrams 12 13 14 and 15 16 17 with appurtenant tables give the results of these measuring methods performed on the traction series and on the bed rest series

In the traction series 72 per cent of the patients had joint surface quotients within the normal range in the bed rest series only 62 per cent

[illegible] of the radius quotient showed the corresponding values

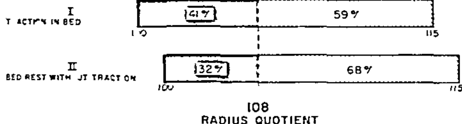


Diagram 17 Distribution of radius qu tients *ab ve and below 108 within the normal range (below 115) in series I and II*
I Traction in bed Refsnæs 1958–59 1 patients
II Bed rest without traction Refsnæs 1953–57 13 patients
(Tables 53 43)

to be 62 per cent in the traction series and 48 per cent in the bed rest series

Thus both measuring methods revealed the most favourable results in the traction series This is further accentuated when the distribution of the joint surface quotients and radius quotients within the normal range in the two series is investigated The result in terms of the joint surface quotient is not only quantitatively but also qualitatively better after treatment with traction than without (Diagram 14) The same applies to measurement of the radius quotient (Diagram 17)

Thus not only measurement of the epiphyseal quotient but also the use of the two methods whose results ought to be of particular prognostic value shows better results in the traction than in the bed rest series

A collected survey of the results of the measurements in the traction series is given in Diagram 18 The corresponding values for the bed rest series are listed in Diagram 6

DISCUSSION OF RADIOLOGICAL ASSESSMENT

Table 15 p 67 gives a survey of the results It is apparent primarily that regardless of which method of assessment is used the results go on improving with the efficacy of the relief from weight bearing

Nowhere does th table show an exception to this rule

If this general t ndency is taken into account—and of course no finding should be left out of consideration—a *statistical calculation* shows that an essential part of the improvements found are statistically

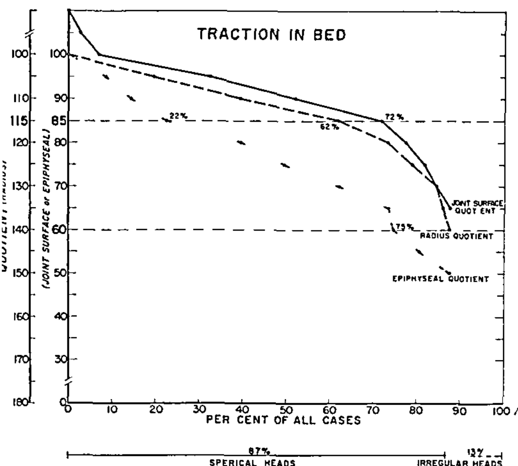


Diagram 18 Epiphyseal quotients joint surface quotients *and* radius quotients
Traction in bed Refsnæs 1958 6? 71 patients
Cf Diagram 6 (Table 51 3)

significant On the other hand if no regard is paid to the tendency apparent *from the table but it is assumed a priori,* that *more effective* relief from weight bearing may give poorer as well as better results—which is hardly realistic or reasonable—only a few of the differences are statistically significant (Appendix III)

However in both forms of statistical calculation—the unilateral test and the bilateral test—the results are influenced by the fact that from a statistical point of view the series are relatively small Mose encountered the same difficulty but met it by combining two bed rest series—although the treatment was not entirely identical—and thus obtained a l rest series of 148 patients Only by comparing this larger series

Table 15 Results obtained by 4 different methods of treatment
Radiological assessment

Treatment	Spherical heads	Epiphyseal quotient above 60	Epiphyseal quotient above 85	Radius quotient below 115	Joint surface quotient above 85
	% of all pts	Moses rule of all pts	Within the normal range % of all pts		
1 Bed rest with traction (71 pts)	87	75	22	62	72
2 Bed rest without traction (79 pts)	73	59	14	48	62
3 Ambulatory relief from weight bearing (64 pts)	61	42	11		
4 Symptomatic or no treatment (70 pts)	19	8	0		

EPIPHYSEAL QUOTIENTS

QUOTIENT

100 90 85 80 70 60 50 40 30 0

NORMAL CHILDREN (80)

8% 42% 59% 75%

I TRACTION IN BED

II BED REST WITHOUT TRACTION

III AMBULATORY TREATMENT

IV SYMPTOMATIC OR NO TREATMENT

0 10 20 30 40 50 60 70 80 90 100%

PER CENT OF ALL CASES

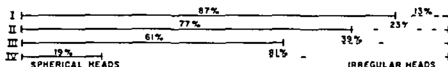


Diagram 19 Epiphyseal quotients *in 6 series treated by 4 different methods (a total of* 413 patients*)*

I	*Traction in bed Refsnæs 1958–63*	*71 pts*
II	*Bed rest without traction Collected series*	*208 pts*
	Hornbæk 1953–57 (measured by Mose) 70 pts	
	Refsnæs 1953–57 (measured by J.M.) 79 pts	
	Refsnæs 1941–50 (measured by Helbo) 59 pts	
III	*Ambulatory treatment (measured by Mose)*	*64 pts*
IV	*Symptomatic or no treatment (measured by Helbo)*	*70 pts*
	Total	*413 pts*

Cf Diagram 7 (Table 53 11 6 8)

with the ambulatory series did he succeed in demonstrating a statistically significant difference between the results of the two forms of treatment.

I have tried to repeat Mose's procedure—with the difference that our bed rest series is supplemented not only with Mose's series from Hornbæk but also with Helbo's from Refsnæs treated during a period immediately preceding that under discussion. This gave a bed rest treated series of 208 patients in which the result in terms of the epiphyseal quotient is practically identical with that in our smaller bed rest series of 79 patient (Diagrams 19 and 20, Table 11).

If the statistical calculations are carried out using this combined bed rest series, the most reasonable way of calculating—the unilateral test—reveals that all improvements in respect to *spherical shape* and *epiphyseal quotient exceeding 60* are statistically significant. Traction is definitely better than bed rest, bed rest better than ambulatory treatment, and ambulatory treatment better than no treatment (Tables 19, 20, 21).

If the stricter—but more theoretical, less realistic calculation—the bilateral test is used, the improvements are also statistically significant, only less so and not including the number of patients with spherical heads in the traction series compared with corresponding patients in the bed rest series. If comparison is made with the ambulatory series the improvement is highly significant—also by this way of calculation.

The number of patients with epiphyseal quotients exceeding 85 shows exactly the same tendency as in the other methods of assessment—increasing relief from weight bearing, better results—but the improvements are not statistically significant by either manner of calculation. The number of patients having epiphyseal quotients in excess of 85 is too small in all the series. A reliable statistical assessment would require a much larger material.

Measurements of the radius quotient and joint surface quotient also records better results with more effective relief from weight bearing—i. e. better *with* than *without* traction—but these differences too are not statistically significant by any form of calculation. In part the series are too small—and cannot yet be supplemented—and in part the improvements obtained by traction, measured by the radius quotient and joint surface quotient, are in fact on the average less marked than when measured by the epiphyseal quotient (Table 22).

Only a considerable increase in the number of patients treated by

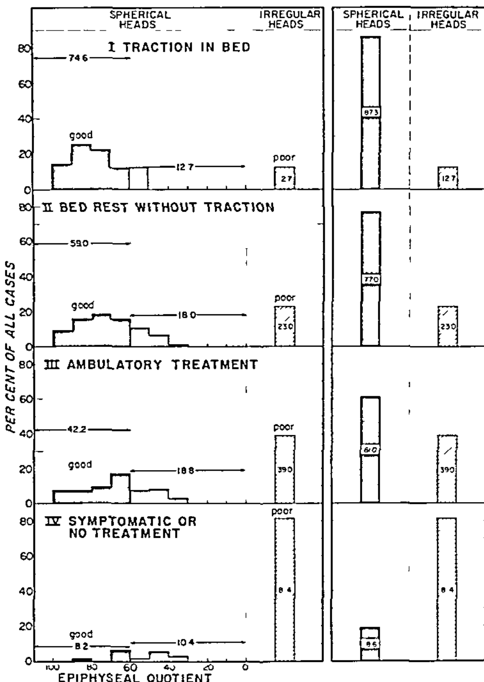


Diagram 90 Distribution of patients with spherical and patients with non spherical (irregular) heads and distribution of epiphyseal quotients above and below 60 i pa i nts with spherical hea ls in 6 series (a total of 513 patients) treated by 4 l ff rent m thods (f legend to Diagram 19 (Tables 51 11 G 8)

traction and measurement of the joint surface quotient and/or radius quotient in a larger number of patients treated with bed rest alone can be hoped to afford a decision as to whether the improvement obtained by traction and measured by the radius quotient and joint surface quotient is statistically significant

But on the whole the statistical analysis has demonstrated that the constant improvement in the results after a more effective relief from weight bearing is in fact statistically significant in such important respects and by so many different methods of assessment that it cannot be due to chance

It must be justified to conclude that the favourable effect of a more effective relief from weight bearing is an established fact

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However a look at the figures obtained by measuring the epiphyseal quotient and those obtained by measuring the joint surface quotient and the radius quotient discloses two striking differences

(1) *After a given therapeutic method the number of good results*—cases within the normal range—is far smaller measured by the epiphyseal quotient than when measured by the radius quotient and in particular by the joint surface quotient (with traction *e g* 22 per cent 62 per cent 72 per cent) (Table 15 p 67)

(2) The *improvement* of the therapeutic results with more effective relief from weight bearing is considerably less pronounced when measured by the radius quotient and joint surface quotient than when measured by the epiphyseal quotient (Table 16)

Table 16 Improvement in per cent obtained by treatment with traction in bed *compared with* bed rest without traction *calculated at various levels of epiphyseal quotient radius quotient and joint surface quotient*

Epiphyseal quotient Joint surface quotient	>60	>65	>70	>75	>80	>85	>90
Radius quotient	<140	<135	<130	<125	<120	<115	<110
	%	%	%	%	%	%	%
Improvement measured by							
Epiphyseal quotient	27	38	44	53	56	57	55
Radius quotient	19	17	21	18	22	29	39
Joint surface quotient	19	19	15	14	15	16	18

The explanation of the former difference has been mentioned several times above in discussing the advantages and disadvantages of measuring the epiphyseal quotient and the joint surface quotient (radius quotient)—but perhaps it should be briefly summed up

The epiphyseal quotient is a measure of epiphyseal flattening Epiphyseal flattening is considerable in all forms of treatment and it is only in a few cases that the measurements can be kept within the normal range

Epiphyseal flattening is counteracted by the compensatory growth processes in the femoral head which often succeed despite considerable epiphyseal flattening in keeping the shape of the head within the range of normal

As the joint surface quotient and the radius quotient measure the shape of the head the great majority of cases measured by these methods will be within the normal range

The *latter phenomenon* has not been discussed before

That improvements obtained by a more effective relief from weight bearing are more marked measured by the epiphyseal quotient than by the joint surface and radius quotient is apparent from Table 16 (p 71) and Diagram 21 which show that the curves representing the joint surface quotients in the two series in which these quotients were measured are far closer than the corresponding curves representing epiphyseal quotients The same applies to the curves representing the radius quotients

The explanation is to be found in the same factors which made the epiphyseal quotients after the same treatment record far more pronounced deviations from normal than the joint surface quotients and radius quotients

If a less effective treatment is instituted this is immediately reflected in the epiphyseal quotients epiphyseal flattening being increased while the joint surface quotient and the radius quotient show little reaction as the compensatory processes included in these two measurements set in and counteract the flattening

Reversely When changing to better treatment the epiphyseal flattening will immediately be diminished and the epiphyseal quotient consequently improved—in some cases considerably If the compensatory processes during the inferior form of treatment have been very effective there will be only little improvement in the shape of the head —and thereby in the joint surface and radius quotients—possibly none nl liminished flattening of the epiphysis

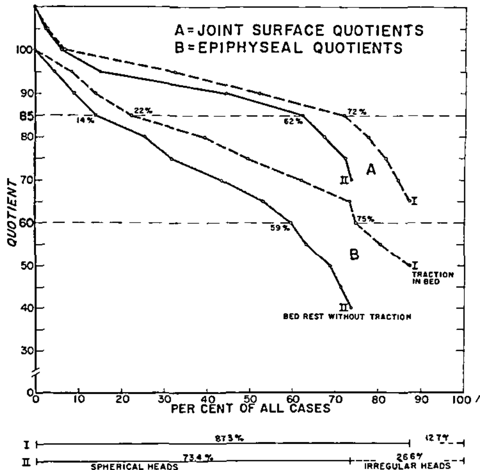


Diagram 21. The improvement in the therapeutic result obtained by traction in bed compared with bed rest without traction is greater measured by the epiphyseal quotient *(lower shaded area) than measured by the* joint surface quotient *(upper shaded area). (Cf. Table 16)*

I. Traction in bed. Refsnæs 1958–69. 71 patients.

II. Bed rest without traction. Refsnæs 1953–57. 79 patients.

(Tables 5, 4, 51, 41)

In brief: The compensatory processes act as a regulator on the reaction of the joint surface quotient and radius quotient, while the epiphyseal quotient fluctuates unimpeded in step with the epiphyseal flattening.

Therefore it is easy to understand that we found less marked diffe

rences in joint surface and radius quotients than in the epiphyseal quotients when the treatment improved

These calculations—and the curves on Diagram 21—are to some extent influenced by the fact that the number of cases with spherical heads increases with the use of traction This influence may be eliminated by fixing the number of spherical heads as 100 per cent in both series

It turned out that this did not alter the conclusion

We have now analysed what can be elucidated by a radiological assessment of the results obtained by various therapeutic methods

The most important finding is that the *radiological results improve with increasing efficacy of the relief from weight bearing* This rule applies without exception to all methods of assessment and all methods of treatment (Table 15 p 67) The best results are obtained by treatment with traction in bed

When the evaluation is based upon the number of spherical heads and epiphyseal quotients exceeding 60 the improvements are statistically significant throughout

When the assessment is based upon the figures representing epiphyseal quotients joint surface quotients and radius quotients exceeding 85 the improvements are not statistically significant In the first place the number of patients having epiphyseal quotients in excess of 85 and the series measured by the radius quotient and joint surface quotient are too small In the second place the differences measured by the joint surface quotient and radius quotient are in actual fact smaller than those measured by the epiphyseal quotient

The latter is not merely of theoretical interest but of great importance in any prognostic discussion The fact is that judging by all findings the prognosis depends upon the shape of the femoral head—and this is what is measured by the joint surface quotient and the radius quotient Therefore the finding that improvements in the therapeutic results are less marked when measured by the joint surface quotient and radius quotient than by the epiphyseal quotient means that *from a prognostic point of view the improvement is less marked than indicated by the measurement of the epiphyseal quotient* The epiphyseal quotient is an expression of the efficacy of the treatment in preventing the epiphyseal flattening not of the prognosis

The ultimate question is then which of the two methods of assessment—the radius quotient which measures the shape and size of the head or the joint surface quotient which only measures the shape—is more relevant in assessing the prognosis According to my estimate it is the joint surface quotient as the size of the head is presumably of less prognostic importance

On the basis of the joint surface quotients 72 per cent of the cases treated with traction have a favourable prognosis—as compared with 62 per cent after treatment by bed rest alone

Thus the measurement of the joint surface quotient sorts off the cases which have a *good* prognosis By dividing the material into cases with spherical and with non spherical heads it is possible to sort off cases with a *poor* prognosis—*i e* cases with irregular heads Of course this can also form the basis of a prognostic assessment After treatment with traction 13 per cent of the patients will have irregular heads—and therefore a poor prognosis—as compared with 27 per cent after treatment with bed rest alone 39 per cent after ambulatory treatment and 81 per cent when no treatment is instituted The two forms of radiological assessment supplement each other Both afford information of interest—but in general most interest is taken in the number of successful results

However all these prognostic predictions are mere hypotheses based on a radiological assessment

In the last chapter it will be endeavoured to establish the actual relation between the radiological assessment and the clinical course of the disease—*i e* the symptoms and signs at the time of primary healing and the prognosis at longer sight

Clinical Assessment of the Various Forms of Treatment

In this section the word *symptoms*, which will be encountered over and over again, is used as a designation of *all* forms of clinical manifestations—subjective as well as objective.

Subjective clinical manifestations will be called *subjective symptoms*, meaning all complaints, regardless of whether or not an objective basis is demonstrable.

Objective clinical manifestations will be called *objective signs*, meaning all divergences from normal which are—or can be—demonstrated by physical examination.

The result of an investigation of the frequency of symptoms in a group of patients depends, of course, entirely upon the examiner's energy and interest in the matter.

At the time of primary healing of LCPD the patients are usually children in the age range 6–10 years. In such patients the subjective symptoms are very few and, as a rule, they can only be disclosed by interviews with the parents—who are not always good observers (or listeners!). On the other hand, an efficient and experienced examiner can nearly always find objective signs of past disease. As a rule, such signs are not outstanding, but they are present in almost 100 per cent of the cases.

It is evident, therefore, that analyses of the frequency of symptoms *after the course of a LCPD will give extremely different results* when done by different persons. Accordingly, statements in the literature should be regarded with criticism.

Helbo states that 26 per cent of his patients who were treated with bed rest had "symptoms" at the time of primary healing. An attempt was also made to assess our bed rest series for "symptoms" at this juncture. We found the rate to be 57 per cent. The majority of these symptoms were very modest—an explanation of the general opinion that LCPD heals *without* symptoms. Since presumably there is not a real difference between Helbo's series and ours, the discrepancy be-

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30–50 years and the osteoarthritis had appeared at approx 20–40 years of age

It must be added however that 30–50 years is a very early age for analysing the *final* number of cases of osteoarthritis If Helbo s patients are after-examined 50 years or longer after the onset of the disease *i e* at an age of 60 or over a considerably larger proportion will show signs of osteoarthritis However it must then be realized that at this age osteoarthritis may also be present in persons whose history is negative for hip disease

The figures representing the clinical prognosis in Table 17 p 81 then carry some uncertainty partly owing to the special nature of Helbo s follow up series and partly because they apply only to the prognosis up to the age of 30–50

A more reliable assessment of the prognosis in more effectively treated series presupposes a follow up on a treated series in which a large proportion of the cases have healed primarily with spherical heads—and preferably the follow up period should be longer than Helbo s

However this cannot be done in this country until a late follow up on Helbo s patients treated with bed rest in 1940–50 is possible—*i e* some time towards the end of the century

Table 18 *Total result—4 methods of treatment*

Method of treatment	No of treated pts	Radiological assessment at time of primary healing: Practically normal heads: Mose epiph quot >60	Practically normal heads: IM joint surf quot >85	Spherical heads	Non spherical heads	Clinical assessment. Expected clinical condition after a follow up period of at least 25 years according to Helbo s follow up study: expected osteo arthritis	expected symptoms (osteo arthr and not osteo arthr)	expected number of symptom free pts
		%	%	%	%	%	%	%
I Traction in bed	71	75	72	87	13	10	12	88
II Bed rest without traction	79	59	62	73	27	20	24	76
III Ambulatory relief from weight bearing	64	42		61	39	30	35	65
IV No or symptomatic treatment	70	8		19	81	62	73	27

% signifies % of treated patients in the series concerned

criticism of the epiphyseal quotient as an expression of capital shape cf p 40 ff

Table 18 Total result—4 methods of treatment

Method of treatment		No of treated pts	Radiological assessment at time of primary healing: Practically normal heads: Mosc epiph quot >60	Practically normal heads: J M joint surf quot >8[illegible]	Spherical heads	Non spherical heads	Clinical assessment: Expected clinical condition after a follow up period of at least 25 years according to Hellbo's follow up study: expected osteo arthritis	expected symptoms (osteo arthr and not osteo arthr)	expected number of symptom free pts
			%	%	%	%	%	%	%
I	Traction in bed	71	75	72	87	13	10	12	88
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III	Ambulatory relief from weight bearing	64	42		61	39	30	15	65
IV	No or symptomatic treatment	70	8		19	81	62	73	27

% signifies % of treated patients in the series concerned
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division is of significance in assessing the prognosis Cases healing with irregular heads are sure to have a *poor* prognosis cases with spherical heads a better prognosis but prognostically they make up a far more mixed group As they occur in large numbers after one of the more effective methods of treatment this group requires a closer analysis

This can be done firstly by measuring the *joint surface quotient* which is a direct expression of capital shape This measuring method too is then of importance in assessing the prognosis mainly as it makes it possible to pick out a group of cases having a *definitely favourable* prognosis viz cases which have healed with a femoral head whose shape is within the range of normal

The group of cases with spherical heads may also be assessed by measurement of the *radius quotient* This quotient is directly proportional to the size as well as the shape of the head Therefore it presumably gives too pessimistic a basis for assessing the prognosis The size of the head is not of as much prognostic importance as its shape

Measurement of the *epiphyseal quotient* does not afford an expression of the shape of the femoral head but of the shape of the epiphysis Accordingly the results of this measurement are not suited for prognostic assessment On the other hand they afford an excellent sensitive indicator of the ability of treatment to prevent epiphyseal flattening

Application of these radiological measuring methods to the result of 4 different therapeutic methods gives a number of figures representing the number of cases having a *favourable and a poor prognosis* and the number of cases with *flattened and less flattened epiphyses* The significance of these figures is radiologically well defined and they represent the results of measurements which can be performed with considerable accuracy But whether the percentages for a good and for a poor prognosis found by these measurements actually do indicate the long term clinical prognosis after the various therapeutic methods is a question which cannot be answered just so But anyway together with the results of measuring the epiphyseal quotient they no doubt form a reliable basis for assessing the *relative* efficacy of the various methods of treatment

The four methods of treatment are

I Relief from weight bearing by bed rest with traction
II Relief from weight bearing by bed rest without traction

III Ambulatory relief from weight bearing
IV No or only symptomatic treatment

The efficacy of the relief from weight bearing increases from treatment IV to treatment I

The radiological measurements revealed that the values which were to indicate the prognosis improved considerably the more effective the relief from weight bearing had been

The number of *spherical heads* is about 4 times larger after traction than after treatment without relief from weight bearing (all differences in the number of spherical heads are statistically significant)

The number of cases with practically normal heads found by measuring the *joint surface quotient* could regrettably not be established for all 4 therapeutic methods but only following treatments I and II This is the more unfortunate as measurement of the joint surface quotient is the only method which affords information concerning the number of cases having a definitely good prognosis Grouping into cases with spherical and with non spherical heads affords information primarily about the number of cases having a *poor* prognosis The two measuring methods whose results influence the prognostic assessment give information concerning different aspects of the prognosis and must be said to supplement each other

The number of cases with practically normal heads determined by measuring the joint surface quotient is 16 per cent larger after treatment with traction than after treatment with bed rest without traction The number of spherical heads is 19 per cent larger (The latter difference is statistically significant)

When looking at the result of measuring the *epiphyseal quotient*, which expresses the ability of the treatment to prevent epiphyseal flattening we find the improvement with increasing relief from weight bearing to be greater still than indicated by the values supposed to represent the prognosis The group of least flattened epiphyses (epiphyseal quotient > 60) is about 10 times larger after treatment with traction (I) than after treatment without relief from weight bearing (IV) This indicates that—as expected—the epiphyseal quotient is not a measure of the prognosis but merely of the therapeutic effect upon the epiphysis

Thus the radiological assessment has shown without leaving any room for doubt that the efficacy of the treatment increases with increasing relief from weight bearing Treatment by relief from weight

bearing is better than treatment without relief from weight bearing Relief from weight bearing by bed rest without traction is better than ambulatory relief from weight bearing and relief from weight bearing by bed rest with traction is the best method

As already mentioned this simple conclusion concerning the relative efficacy of the therapeutic methods may in my opinion be drawn with great certainty It is based on objective simple radiological measurements and is independent of inaccurate disputable clinical definitions of good and poor results

However it concerns only the *relative* value of the methods It does not say anything about the validity of the actual prognosis set up for each treatment series on the basis of the radiological assessment at the time of primary healing

The problem was then Are these absolute percentages found for the number of cases having a favourable prognosis in accordance with the actual clinical course after the various methods of treatment?

In an endeavour to answer this question it was tried by means of a late clinical follow up conducted by Helbo to establish the clinical prognosis for the radiological types described in the present paper This was hoped to confirm the prognoses set up exclusively on a radiological basis

In other words it was attempted to check the radiological assessment clinically

The report on this analysis may be restricted to the prognosis following treatment with traction in bed The relation to the other forms of treatment is apparent from what has been stated above

The following findings were made

In the radiological assessment it was estimated that after treatment with traction 72 *per cent* of the patients had a good prognosis

The radiological criterion of a good prognosis was that measurement of the *joint surface quotient* showed the shape of the femoral head to be within the range of normal If this criterion is observed one need not at least fear that the prognostic assessment will be too favourable On the contrary it is probable that a number of patients with capital shapes which differ definitely—but only to a slight extent—from normal will also prove to be symptom free even at a late follow up examination

Thus the 72 per cent represent a minimum value

At the clinical assessment it was found that *88 per cent* of the patients treated with traction would presumably remain symptom free

But the basis of the clinical assessment was Helbo s follow up on a series of a nature entirely different from that which would be available after treatment with traction It has been stated that if conclusions drawn on the basis of this follow up study are used for assessing the prognosis following treatment with traction there will be *two sources of error* In part the large number of cases healing with spherical heads after traction will be assessed too favourably and in part the prognosis for cases with irregular heads will be assessed too pessimistically

These sources of error involve an uncertainty in assessing the prognosis following treatment with traction but possibly the two sources of error will eliminate each other

But one thing is beyond doubt Helbo s follow up study was conducted when the patients were 30–50 years of age This mere fact makes his conclusions concerning osteoarthritis *too optimistic* not only in respect to the final result in his own series but especially when his figures are transferred to a series of patients treated with traction Osteoarthritis does not develop until a late date in the large number of patients with slightly deformed heads found after this form of treatment

Thus the clinical assessment of the prognosis following traction is presumably too optimistic To remain on the safe side we must stick to the 72 per cent good results found by the radiological assessment

Presumably, the truth lies somewhere between 72 per cent and 88 per cent

The object of a future study then must be to *approach these two figures to each other, i e* to obtain greater accuracy in assessing the clinical long term prognosis on the basis of the primary radiological result

However this can only be done if we have access to a treated series healed with a high percentage of spherical heads and thereafter followed closely radiologically as well as clinically for at least 25 years preferably longer

In this country the result of such a follow up study will not be available until it is possible to carry out such a late follow up on the patients treated in 1940–50 with bed rest at the Seaside Hospital Refsnæs (Helbo) This will not be until some time towards the close of the century

Until then most importance must be attached to a careful radio

logical description at the time of primary healing dividing the cases into spherical and non spherical heads measuring the epiphyseal quotients and in particular the joint surface quotients etc

The result of such measurements is at any rate very well suited for *comparative* assessment of various therapeutic methods and as a basis for a preliminary prognostic estimate at the time of primary healing

When more relevant follow up studies become available the prognosis may perhaps be estimated with greater accuracy

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For bilateral cases cf Appendix I

APPENDIX I

The Bilateral Cases

The studies reported in this paper concern exclusively *unilateral* cases of LCPD which usually make up 90–95 per cent of the patients referred for treatment

The bilateral cases were not included in the analysis as the radio logical measuring methods used in evaluating the unilateral cases are not *applicable in bilateral cases* There is no normal side for comparison True bilateral cases *may* be assessed by altering the me thods but this makes the results less accurate

But as a matter of fact there is nothing to indicate that the joints in bilateral cases might be influenced by relief from weight bearing in any way different from the joints in the unilateral cases Therefore if a radiological assessment could be applied to a material in its entirety—*i e* a collected assessment of bilateral and unilateral cases —the result is not likely to be much different from that of a radio logical assessment of the unilateral cases only This of course pre-supposes that bilateral involvement is not connected with any special —favourable or unfavourable—radiological types This is difficult to estimate before a larger number of bilateral cases is available All considered however I do not believe that our radiological assessment of the efficacy of the various therapeutic methods on the basis of the unilateral cases would alter materially had a detailed radiological assessment of the bilateral cases been possible

From a clinical point of view however this is different

Given two series which after treatment are radiologically identical we would find that the one which contained the larger number of bilateral cases would be clinically more unfavourable

After treatment with bed rest the number of bilateral cases will be approx 8 per cent corresponding to the number on referral while after ambulatory *relief from weight bearing and presumably also after* symptomatic (or no) treatment it will be considerably larger The fact is that *during* treatment of unilateral cases with bed rest no new bi lateral cases will arise while this occurs in another 8 per cent or so

among the unilateral cases treated with unilateral ambulatory relief from weight bearing (Mose) In other words after this ambulatory treatment the number of bilateral cases will be twice that after treatment with bed rest

Thus even if the radiological result after ambulatory relief from weight bearing and after bed rest were the same the clinical result after ambulatory treatment would be poorer But the radiological result after the two methods of treatment is not the same—it is poorer after ambulatory treatment This is enough to make the clinical result after ambulatory relief from weight bearing poorer—but then the effect of the larger number of bilateral cases is superadded

Thus there is every reason to think twice if one feels tempted—out of economical social or humane regards—to try ambulatory relief from weight bearing by a Thomas brace or the like

APPENDIX II

Joint Surface Quotient — Radius Quotient

As regards the relationship between the joint surface quotient and the radius quotient after treatment for LCPD it may be said in more detail

The *flattening* makes the *radius* of the femoral head longer its *height* lower

The *increase in growth* makes the *radius* as well as the *height* of the head greater

---

Joint surface quotient $= k_1 \times \frac{H}{R}$ where H and R are the height and *radius of the diseased head* k_1 *a constant based upon the measurements on the sound side*

Radius quotient $= k_2 \times R$ where R is the radius on the diseased side k_2 a constant based on the measurement on the sound side

---

From this it is apparent that

the *flattening* affects the joint surface quotient *more* than the radius quotient R becomes larger H smaller

the *increase in growth* affects the radius quotient *more* than the joint surface quotient H is not included in the radius quotient

---

In all cases treated with any success the increase in growth will completely predominate over the flattening so that the height H will be *increased* despite the flattening Only in the case of great flattening will the height be the same on both sides—in rare cases possibly smaller on the diseased side

As the increase in the growth of the head (and adjacent bony areas) plays an important role in all cases of LCPD the consequence is that

in mild and moderate flattening the radius quotient shows a much greater response than the joint surface quotient—viz it gives a stricter assessment of the result Not until very marked flattening do the heights (H) become equal and both measurements therefore dependent only upon the radius (R)—their difference from normal will be the same

This is the explanation why the number of cases below the normal maximum or above the normal minimum is smaller when the radius quotient than when the joint surface quotient is measured

Calculation and Plotting of the Radius Quotient

With increasing deformation of the head the radius quotient increases while the joint surface quotient decreases On the diagrams however the curve representing the radius quotients is turned so that it is on the same side of the normal value (100) as the curve representing the joint surface quotient (i e below the normal value) This facilitates the incidentally very problematic comparison of the radius quotient with the joint surface quotient

If such a plotting of the radius quotient is to be maintained it is more correct to calculate the radius quotient as $\frac{r}{R}$ falling with increasing R deformity—rather than as $\frac{R}{r}$ True this makes the deflections on the diagrams (and tables) rather less marked than the use of $\frac{R}{r}$ but as the variation in normal children also becomes less marked there will be no change in the number of cases within the normal range in the two series

Since it is more practical for several reasons to calculate the radius quotient as $\frac{R}{r}$—int al in order to avoid different values for the normal variation of the radius quotient and joint surface quotient—this manner of calculation and plotting of the radius quotient was maintained

Logarithmic plotting of the radius quotient $\left(\frac{R}{r}\right)$ and joint surface quotient also makes the two sets of values more comparable—but it also makes it difficult to give a clear graphic representation

Appendix III

Comments on Statistical Calculation

By SVEND SORENSEN M.Sc. (econ.)

The tests were carried out as a comparison of the frequency of a given therapeutic result following two methods of treatment according to the formula

$$u = \frac{\left(h_1 - \frac{1}{2n_1}\right) - \left(h_2 + \frac{1}{2n_2}\right)}{\sqrt{h(1-h)\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}$$

$$h_1 = \frac{x_1}{n_1} \quad h_2 = \frac{x_2}{n_2} \quad h = \frac{x_1 + x_2}{n_1 + n_2} = \frac{x}{n}$$

in which x_1 is the number of patients obtaining a given therapeutic result by treatment 1 and x_2 the number of patients obtaining the same therapeutic result by treatment 2. n_1 and n_2 are the total number of patients subjected to treatment 1 and treatment 2 respectively.

The comparison between bed rest *with* traction and bed rest *without* traction was performed as a unilateral as well as a bilateral test. In the unilateral test, taking support in the available numerical material, the possibility that bed rest with traction could be inferior to bed rest without traction was ruled out. In the unilateral test the alternative to bed rest with traction being a better form of treatment than bed rest without traction is that the two methods are equally good. As it was not possible *a priori* to rule out the possibility that bed rest with traction is inferior to bed rest without traction, the presupposition of using this procedure was, strictly speaking, not fulfilled. Therefore the test was also performed as a bilateral test. For the same reasons the comparison between bed rest with traction and ambulatory treatment and between bed rest without traction and ambulatory treatment was also carried out by unilateral as well as bilateral tests.

Summary

After criticising the radiological methods used so far for assessing the results of treating Legg Calve Perthes disease (LCPD) the author tries to arrive at a suited method based upon the principle that the shape of the femoral head is of decisive prognostic importance

The normal and the pathological radiological appearances are de scribed and discussed It is established that the first step in the radio logical assessment of the therapeutic result at the time of primary healing about a year or two after the discontinuation of treatment should always be a classification of the series into cases having *sphe rical femoral heads* and others having *irregular non spherical heads* This can now be done with greater objective accuracy than before by means of the plastic plate with concentric circles used by Mose According to the named principle cases with spherical heads have a better prognosis than cases with irregular heads whose prognosis is definitely poor

This should be followed by a closer assessment of the very large group of cases which after effective treatment have healed with spherical heads Attempts to do so revealed that measurement of the *epiphyseal quotient* which reflects the flattening of the epiphysis was an excellent indicator of the effect of treatment upon the shape of the epiphysis On the other hand measurement of the *joint surface quotient* which reflects the shape of the head proved best suited for a prognostic assessment Cases whose joint surface quotients were within the normal range must have a good prognosis

The *radius quotient* reflects the *shape* as well as the *size* of the head and accordingly gives a stricter—and presumably too pessimistic —evaluation of the prognosis

Thus the radiological measurements each describe given—but mu tually different—qualities of the radiological appearance The shape of the femoral head the shape of the epiphysis etc Together they afford an all round picture of the primary results but measurement of the joint surface quotient gives the best guidance in assessing the number of cases having a good prognosis

After these introductory—and of necessity rather detailed chapters—the radiological methods of assessment were applied to the results of 4 therapeutic methods

I Bed rest with traction
II Bed rest without traction
III Ambulatory relief from weight bearing
IV No or only symptomatic treatment

The efficacy of the relief from weight bearing increases from treatment IV to treatment I

Measurement of the joint surface quotient could only be carried through in series I and II The measurements of the epiphyseal quotients in series IV and III had been performed by Helbo and Mose but were indirectly checked by the present author

From the various measurements it was apparent that the radiological results improved as the efficacy of relief from weight bearing increased

The number of spherical heads increased from series IV to series I as follows (per cent of all patients in the series concerned)

19 per cent 61 per cent 73 per cent 87 per cent

The number of cases having epiphyseal quotients above 60 increased as follows

8 per cent 42 per cent 59 per cent 75 per cent

and the number of cases having joint surface quotients within the normal range (above 85) increased from series II to series I as follows

62 per cent 72 per cent

It is apparent from these last two figures that the shape of the head—which decides the prognosis—improved less (62–72 per cent) than the epiphyseal shape (59–75 per cent) on transition from bed rest without traction to bed rest with traction And this is just what was to be expected when bearing in mind the activity of the compensatory processes in the presence of greatly flattened epiphyses

All the figures show that treatment with traction—compared with the other 3 methods of treatment—gives the best radiological results

After traction at least *72 per cent* of the treated cases must be presumed to have a favourable prognosis

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Finally an attempt was made to ascertain whether these radiological assessments and predictions were in conformity with the clinical findings—in *brief* an attempt at a clinical check on the radiological assessments

This is difficult—and the result is uncertain

At *the time of primary healing of LCPD* the patients are not as generally assumed symptom free but the detection of the symptoms and their frequency depends entirely upon the intensity of the examination and the definition of the concept symptoms

Examining patients after treatment with bed rest Helbo found primarily symptoms in 26 per cent while the present author found symptoms in 57 per cent This difference is due essentially to a difference in the definition of symptoms —mine being more spacious than Helbo s and comprising also milder symptoms

Subjective symptoms were found after treatment with traction in 13 per cent and after bed rest alone in 22 per cent The percentage of objective signs—some of which were very mild—was approximately the same after these two methods of treatment

These symptoms were not as might perhaps be expected restricted to the poorest radiological group but in the present study distributed over *all* groups although they were most common in patients with irregular femoral heads and uncommon in the group of practically normal heads

A clinical check on the *prognoses* set up on the basis of the radiological appearances presupposes a late clinical follow up study

I am aware of only one clinical examination of patients treated for LCPD 25 years or longer after the onset of the disease in which the *late symptoms can be related to the primary radiological types* described in the present paper

This is a series of 47 patients who had received no or only symptomatic treatment and who were after examined by Helbo

In this small series he found *secondary osteoarthritis* in *68 per cent* and symptoms (with or without osteoarthritis) in *81 per cent* According to Helbo all these cases belonged to the group with irregular heads

(Helbo's groups with flattened and irregular heads)—of which they made up 76 per cent and 90 per cent

If the result from the small follow up series is transferred to the 4 series described in the present paper the following incidences of osteoarthritis and of symptoms are to be expected at the end of 25 years

Osteoarthritis	62%	30%	20%	10%
Symptoms	73%	35%	24%	12%

decreasing from no or symptomatic treatment to treatment with traction in bed

For various reasons it is doubtful whether it is justified to apply Helbo's figures to our series but according to close consideration the resulting errors cannot be of decisive importance and at any rate there are no other applicable follow up studies

Thus according to the best clinical assessment which can be done at present only 10 per cent of the patients treated with traction need fear the development of secondary osteoarthritis while *88 per cent* will remain symptom free

According to the radiological assessment we dared not estimate more than *72 per cent* good results

The cause of this divergence is naturally that the radiological assessment was performed with great—perhaps too great—caution and that the clinical assessment was done on the basis of Helbo's follow up study on a series which in essential respects differs from our traction series and therefore is presumably a little too optimistic

Presumably the truth lies somewhere between 72 per cent and 88 per cent

It must be our future endeavour to approach these two figures to each other—*i e* to obtain greater certainty in estimating the clinical long term prognosis on the basis of the primary radiological result

In an effectively treated series however this can be done only if we have access to a treated series healed with a larger number of spherical heads and thereafter closely followed radiologically as well as clinically for at least 25 years preferably longer

Such a series will not be available in this country until the end of this century

Tables

Table 1. Patients treated with prolonged bed rest without traction *at Refsnæs 1953–57 (79 patients)*
Age distribution and stage at institution of treatment (per cent of all cases)

1–4 years	5–8 years	9–12 years
26 %	61 %	13 %

Early condensation without flattening	Late condensation with flattening	Fragmentation
45.6 %	26.6 %	27.8 %

Table 2. 3 series—3 therapeutic methods
Patients ages at institution of treatment (per cent of all cases)

	1–4 years %	5–8 years %	9–12 years %
Prolonged bed rest with traction (71 pts.)	34	50	16
Prolonged bed rest without traction (79 pts.)	26	61	13
Ambulatory relief from weight bearing (71 pts.)	39	54	7

Table 3. 3 series—3 therapeutic methods
Stage of disease at institution of treatment (per cent of all cases)

	Early stage (condensation) %	Late stage (fragmentation) %
Prolonged bed rest with traction (71 pts.)	62	38
Prolonged bed rest without traction (79 pts.)	72	28
Ambulatory relief from weight bearing (71 pts.)	78	22

(Helbo's groups with flattened and irregular heads)—of which they made up 76 per cent and 90 per cent.

If the result from the small follow-up series is transferred to the 4 series described in the present paper, the following incidences of osteoarthritis and of symptoms are to be expected at the end of 25 years:

Osteoarthritis	62%	30%	20%	10%
Symptoms	73%	35%	24%	12%

decreasing from no or symptomatic treatment to treatment with traction in bed.

For various reasons it is doubtful whether it is justified to apply Helbo's figures to our series, but according to close consideration the resulting errors cannot be of decisive importance, and at any rate there are no other applicable follow-up studies.

Thus according to the best clinical assessment which can be done at present only 10 per cent of the patients treated with traction need fear the development of secondary osteoarthritis, while *88 per cent* will remain symptom-free.

According to the radiological assessment, we dared not estimate more than *72 per cent* good results.

The cause of this divergence is naturally that the radiological assessment was performed with great—perhaps too great—caution, and that the clinical assessment was done on the basis of Helbo's follow-up study on a series which in essential respects differs from our traction series and therefore is presumably a little too optimistic.

Presumably the truth lies somewhere between 72 per cent and 88 per cent.

It must be our future endeavour to approach these two figures to each other—*i.e.* to obtain greater certainty in estimating the clinical long-term prognosis on the basis of the primary radiological result.

In an effectively treated series, however, this can be done only if we have access to a treated series healed with a larger number of spherical heads and thereafter closely followed radiologically as well as clinically for at least 25 years, preferably longer.

Such a series will not be available in this country until the end of this century.

Table 5 Epiphyseal quotient—joint surface quotient—radius quotient
Patients treated with traction in bed *Refsnes 1958 62 (71 pts)*

	Number	%
Total patients	71	100
with spherical heads	62	87 3
with non spherical heads	9	12 7

In the group of patients with spherical heads

1			2			3		
Epiphyseal quotient	No of pts	% of all pts	*Joint surface quotient*	No of pts	% of all pt	*Radius quotient*	No of pts	% of all pts
100–96 incl	6	8 5	110–106 incl	[illegible]	2 8	100 104 incl	14	19 7
100–91 incl	10	14 1	110–101 incl	[illegible]	7 0	100 109 incl	28	39 4
100 86 incl	16	22 5	110– 96 incl	23	32 4	100 114 incl	44	62 0
100 81 incl	28	39 4	110– 91 incl	37	52 0	100 119 incl	52	73 3
100 76 incl	35	49 4	110– 86 incl	51	71 8	100 124 incl	56	78 9
100–71 incl	44	62 0	110– 81 incl	55	77 4	100 129 incl	60	84 5
100 66 incl	52	73 2	110– 76 incl	58	81 0	100–134 incl	61	85 9
100 61 incl	53	74 6	110– 71 incl	60	84 5	100–139 incl	62	87 3
100–56 incl	57	80 5	110– 66 incl	62	87 3			
100–51 incl	62	87 3						

Table 6 Epiphyseal quotients in patients treated with ambulatory relief from weight bearing *(Mose)*

	Number	%
Total patients	64	100
with spherical heads	39	61
with non spherical heads	25	39

In the group of patients with spherical heads

Epiphyseal quotient	No of pts	% of all pts
100–96 incl	3	4 7
100–91 incl	5	7 8
100–86 incl	7	10 9
100–81 incl	10	15 6
100–76 incl	13	23 0
100–71 incl	16	25 0
100–66 incl	20	31 2
100–61 incl	27	42 2
100–56 incl	30	47 0
100–51 incl	32	50 0
100–46 incl	34	53 2
100–41 incl	37	58 0
100–36 incl	39	61 0

Table 7 Epiphyseal quotients in patients treated with bed rest without traction *Refsnæs 1941–50 (Helbo)*

	No of pts	%
Total patients	59	100
with spherical heads	45	76 4
with non spherical heads	14	23 6

In the group of patients with spherical heads

Epiphyseal quotient	No of pts	% of all pts
100–96 incl	1	1 7
100–91 incl	5	8 5
100–86 incl	7	11 8
100–81 incl	15	25 4
100–76 incl	16	27 0
100–71 incl	21	35 6
100–66 incl	26	44 0
100–61 incl	32	54 3
100–56 incl	35	59 0
100–51 incl	41	70 0
100–46 incl	42	71 0
100–41 incl	45	76 4

Table 8 Epiphyseal quotients in patients who received symptomatic or no treatment (Helbo)

	Number	%
Total patients	70	100
with spherical heads	13	18.6
with non spherical heads	57	81.4

In the group of patients with spherical heads

Epiphyseal quotient	No. of pts	% of all pts
100-96 incl.	0	0
100-91 incl.	0	0
100-86 incl.	0	0
100-81 incl.	1	1.4
100-76 incl.	1	1.4
100-71 incl.	1	1.4
100-66 incl.	3	4.3
100-61 incl.	5	8.2
100-56 incl.	7	10.0
100-51 incl.	7	10.0
100-46 incl.	10	14.3
100-41 incl.	11	15.7
100-36 incl.	11	15.7
100-31 incl.	13	18.6

Table 9 6 patient series—4 methods of treatment
Patients age at institution of treatment (or at time of diagnosis)

Series	Age		
	>4 years	5-8 years	<9 years
	%	%	%
Traction in bed (Refsnæs, J.M.)	34	50	16
Bed rest without traction (Refsnæs, Mose, J.M.)	26	61	13
Bed rest without traction (Refsnæs, Helbo)	14	67	19
Bed rest without traction (Hornbæk, Mose)	37	52	11
Ambulatory treatment (Mose)	39	54	7
No or symptomatic treatment (Helbo)	12	60	28

Table 14 Epiphyseal quotients in patients treated with bed rest without traction

Collected statistics		
Refsnæs 1953–57 (Mose J.M.)	79 pts	
Hornbæk 1953–57 (Mose)	70 pts	

	Number	%
Total patients	149	100
with spherical heads	115	77.2
with non spherical heads	34	22.8

In the group of patients with spherical heads

Epiphyseal quotients	No. of pts	% of all pts
100–96 incl	10	6.7
100–91 incl	14	9.4
100–86 incl	21	14.0
100–81 incl	37	24.8
100–76 incl	51	34.2
100–71 incl	69	46.3
100–66 incl	84	56.4
100–61 incl	91	61.0
100–56 incl	97	65.0
100–51 incl	104	70.0
100–46 incl	109	73.2
100–41 incl	113	76.0
100–36 incl	115	77.1

Table 19 *Statistical calculation of significance of differences between the results obtained by 4 different methods of treating ICHD assessed by the number of* patients with irregular heads
The difference is considered statistically significant when $p < 0\ 050$

Treatment	Series	*Irregular heads*	Statistical calculation	
			Bilateral test	Unilateral test
Traction in bed	71 pts JM	1? 7	u — 1 71	u — 1 71
Bed rest without traction	208 pts coll ser	?3	p — 0 087	*p — 0 044*
Traction in bed	71 pts JM	19 7	u — 1 [illegible]	u — 1 9?
Bed rest without traction	[illegible] pts Mose JM	*[illegible]7*	*p — 0 055*	*p — 0 0?7*
Bed rest without traction	208 pts coll ser	[illegible]	u — ? 3[illegible]	u — ? 36
Ambulatory relief from weight bearing	64 pts Mose	33	*p — 0 018*	*p — 0 0091*
Ambulatory relief from weight bearing	64 pts Mose	*39*	*u — 4 85*	*u — 4 85*
Symptomatic or no treatment	70 pts Helb	81 4	*p — 0 000012*	*p — 0 000006*
Traction in bed	71 pts JM	19 7	u — 3 33	u — 3 33
Ambulatory relief from weight bearing	64 pts Mose	39	*p — 0 00087*	*p — 0 00043*

Table 22 *Statistical calculation* *Significance of the difference between the results obtained by 2 different methods of treating LCPD assessed by the number of patients having joint surface quotients above 85 and radius quotients below 115*
The difference is considered statistically significant when p < 0 050

Treatment	Series	Joint surface quotient above 85 %	Statistical calculation: Bilateral test	Statistical calculation: Unilateral test
Traction in bed	71 pts J M	72	u = 1 10	u = 1 10
Bed rest without traction	79 pts Mose J M	62	p = 0 270	p = 0 140
		Radius quotient below 115 %		
Traction in bed	71 pts J M	62	u = 1 54	u = 1 54
Bed rest without traction	79 pts Mose J M	48	p = 0 120	p = 0 062

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Studies on
the hand in ulnar nerve paralysis

A clinical-experimental investigation
in normal and anomalous innervation

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Contents

Part I

Introduction

With the increasing interest in reconstructive hand surgery knowledge of the nerves and muscles of the hand is of fundamental importance Considerable contributions in this respect have been made by Foerster (1929) Saikku (1947) Bunnell (1956) Landsmeer (1955 1963) Moberg (1958 1962 1964) and Stack (1962)

Despite these contributions surgeons less experienced in operations on the hand are apt occasionally to miss injuries of the ulnar and median nerves Injuries of the radial nerve on the other hand are more readily recognised

The reasons why these nerve injuries are apt to remain concealed are *firstly* the lack of adequate methods for estimating loss of strength of muscles with nerve injury and *secondly* inadequate knowledge of the functions and muscular movements of the hand

Of the three aforementioned nerves it was the radial nerve that was most commonly damaged in the first world war (Pollock 1919 Foerster 1929) To day however it is the ulnar nerve which is more frequently injured than the other two nerves in members of the armed forces on active service and in the civilian population (af Bjorkesten 1947 Woodhall 1947 Zachary 1954 Zachary and Roaf 1954 Nicholson and Seddon 1957 Bateman 1962 Mumenthaler and Schliack 1965)

Though the literature on lesions of the ulnar nerve is voluminous (Mumenthaler (1961) gives more than 350 references) the investigations on record are based on various types of injury such as pareses and paralyses They are classified according to level and to the patients ages and occupations The interval between the injury and the examinations also varies widely the interval sometimes being sufficient for contractures to develop or for the patients to learn trick movements *i e* various manipulations to compensate the loss of strength of certain muscles (Braithwaite Channel Moore and Whillis 1948) Lesions of the ulnar nerve are also sometimes complicated by local simultaneous fractures and often by lesions of tendons

In such heterogeneous series it is difficult to estimate functional losses after injuries of the ulnar nerve

In the present investigation it was therefore decided to study the effect of induced paralysis of the ulnar nerve on the function of the hand in as homogeneous a series as possible

Plan of the investigation

As mentioned above no simple adequate method was available to measure the strength of hand muscles supplied by the ulnar nerve A suitable method was therefore devised. Under standardised conditions the strength of these muscles was estimated with the subject s lower arm and hand placed in a testing bridge The actual measurement was done with a specially con structed dynamometer (Mannerfelt 1961)

The method was first tried on 100 controls (50 males and 50 females) all university students aged 18 to 29 years.

The strengths of following hand functions and movements governed by the ulnar nerve were studied

1 Pinching grip
2 Palmar adduction of the thumb
3 Radial abduction of the index finger
4 Adduction in the second and fourth interspaces
5 Ulnar abduction of the little finger

It is known that muscle function is sometimes impaired in certain positions of the joints and that actively and passively insufficient muscles are dis tinguished (Hjortsjö 1959) Therefore it cannot be excluded that different positions of the wrist in its radio-ulnar axis can affect also the functions studied in the present investigation It is of course not the position of the joint *per se* that decides such weakening but the consequent position of the muscles and tendons It is known that certain grips are stronger with the wrist extended slightly dorsally (Bunnell 1956) Tests 1 2 and 3 were therefore done with the wrist at different angles Tests 4 and 5 with the wrist in mid position between dorsal extension and volar flexion were per formed with the MP joints in two different angles

Two functions of the hands were included in the investigation a picking up test (Moberg 1958) on time and a more specialised picking up test where the examinee was instructed to pierce a piece of paper a certain number of times with a needle and the time required was noted Finally the strength of the hand was measured with Collin s dynamometer Each subject was examined twice once on day 1 and again on day 13

The next link in the investigation was examination of the effect of ulnar paralysis on the function of the hand A series with clinical ulnar lesions

would be less suitable for this purpose because of the above mentioned complicating and varying factors In order to secure as homogeneous a series as possible it was decided to study the clinic of paralysis of the ulnar nerve in 40 healthy volunteers (university students) and to block the ulnar nerve by intraneural injection of a local anesthetic Carbocain® 1 % without adrenalin The author was included in this material where the age range was otherwise the same as that of the control series

Proper evaluation of muscular weakness because of nerve injury as after nerve blocks in lower arm and hand requires knowledge of the variants of innervation Such variants in the lower arm have long been known An anastomosis of the nerve distally to the acutal level of nerve injury may lead to underdiagnosis of paresis or paralysis The possible occurrence of anomalous innervation was therefore given particular attention in the present investigation Interest was thus focused on the so called Martin Gruber anastomosis between the median and ulnar nerves in the lower arm an anastomosis first described by the Swedish anatomist Martin in 1763

It was therefore motivated to place the intraneural block of the ulnar nerve at a level proximal to the sulcus nervi ulnaris thus at the level of the elbow This level was also chosen for the following reasons

1 It is a common level of clinical injury
2 Block affects the nerve before it has given off any motor branches
3 The nerve is readily accessible for block and electric stimulation
4 Clinical experience suggests that such a blockade is not injurious

With a special electrophysiological technique (Hodes Larrabee and German 1948) it was checked that the block was complete

Under standardised conditions and with the same tests as the control group the persons in the blocked group were examined 4 times They were examined on day 1 and day 7 before and after the block which was induced on day 7 and finally on day 13 The blocked group included a small subgroup which was examined daily for 13 days and the block was likewise induced on the 7th day

As a final step in the examination measurements were made on a small number of patients with clinical ulnar motor lesions and cared for at the Department of Orthopaedic Surgery University Hospital Lund between the years 1962—1964 The measurements were as a rule made in the test bridge with the special dynamometer

Adduction of the thumb appears to be brought about by long extensors and long flexors of the thumb in ulnar nerve paralysis Fick (1845) and Duchenne (1867) believed that the extensor pollicis longus is a main adductor substitute in paralysis of the ulnar nerve Other authors (Villiger Ludwig 1946 Wartenberg 1953 v Lanz Wachsmuth 1959) claim that the

flexor pollicis longus is the main substitute for the adductor Opinions thus differ on this point and it was considered justified to ascertain which of the two muscles the extensor pollicis longus or flexor pollicis longus is the true substitute for the adductor of the thumb on palmar adduction after the induction of total ulnar paralysis of the hand

Problems

An attempt was made to find answers to the following questions

1 Does the strength of the pinching grip palmar adduction of the thumb and radial abduction of the index finger normally vary with the angulation of the wrist in the radio ulnar axis

2 To what extent is the strength of palmar adduction of the thumb radial abduction of the index finger ulnar abduction of the little finger and adduction in the 2nd and 4th interspaces decreased *after* total ulnar block if the radio ulnar axis of the wrist is in midposition between volar flexion and dorsal extension and to what extent is the strength of the pinching grip decreased when the wrist is extended dorsally 30 ?

3 Does the strength of the pinching grip the palmar adduction of the thumb and the radial abduction of the index finger after total ulnar block vary with movement of the wrist about the radioulnar axis?

4 Can any anomalous innervation of Martin Gruber type be demonstrated after total ulnar block?

5 Can Fick s (1845) and Duchenne s (1867) conception be verified that the extensor pollicis longus can act as an adductor substitute and if so how strong is its effect in acute paralysis of the ulnar nerve and to what extent does it vary with the angle of the wrist?

6 Has the flexor pollicis longus any adducent effect on the thumb in acute paralysis of the ulnar nerve?

7 Does intraneural block with 1 % Carbocain® without adrenalin cause any sequelae with consequent loss of strength or sensibility of the hand?

Definitions

ANGLE OF THE WRIST

Dorsal extension about the radio ulnar axis of the wrist is marked + volar flexion — The midposition between dorsal extension and volar flexion is designed ±0° At ±0 position the metacarpal plane II—V is in an

extension of the lower arm which according to the experimental conditions used is in midposition between pronation and supination The elbow joint is then flexed 90

POSITIONS IN MP JOINTS II—V

MP 180 designates extended MP joints MP 120 60 volar flexion

PINCHING GRIP

According to Bunnell (1956) the pinching grip represents a round 0 where the thumb with its distal volar ulnar aspect is in contact with the distal volar radial aspect of the index finger to form a grip (tip pinch)

PALMAR ADDUCTION MOVEMENT OF THE THUMB

In the final phase of palmar adduction the ulnar aspect of the extended thumb is in contact with the volar proximal surface of the extended index finger In the examination bridge the elbow is flexed 90 and the forearm is horizontal and locked in midposition between pronation and supination so that the nail of the thumb in the last phase of movement of palmar adduction is also horizontal At the beginning of palmar adduction when the thumb is abducted it is pronated about 30 Palmar adduction movement can therefore be described as an adduction supination movement

RADIAL ABDUCTION OF INDEX FINGER

MP joint PIP and DIP joints II are extended and the only movement that occurs is about a dorso volar axis in the MP joint II from adduction to full abduction in radial direction

ADDUCTION IN SECOND AND FOURTH INTERSPACES

With MP PIP and DIP joints extended the index finger is adducted towards the middle finger and the little finger towards the ring finger Movement occurs about the respective dorso volar axes of the MP joints

ULNAR ABDUCTION OF THE LITTLE FINGER

In principle this movement is like the radial abduction of the index finger with the difference that abduction occurs ulnarly about the dorso volar axis of the extended MP joint V

Abbreviations

ABD V	M	Abductor digiti quinti
ADD POLL	M	Adductor pollicis
APB	M	Abductor pollicis brevis
APL	M	Abductor pollicis longus
ECRB	M	Extensor carpi radialis brevis
ECRL	M	Extensor carpi radialis longus
ECU	M	Extensor carpi ulnaris
EDC II—V	M	Extensor digitorum communis II—V
FD V P	M	Extensor digiti quinti proprius
EIP	M	Extensor indicis proprius
EPB	M	Extensor pollicis brevis
EPL	M	Extensor pollicis longus
FD V B	M	Flexor digiti quinti brevis
FCR	M	Flexor carpi radialis
FCU	M	Flexor carpi uln
FDP II—V	M	Flexor digitorum profundus II—V
FDS II—V	M	Flexor digitorum sublimis II—V
FPB	M	Flexor pollicis br
FPL	M	Flexor pollicis lo
IOD I—IV	M	Interosseus dorsa I—IV
IOV I—III	M	Interosseus volari I—III
L I—IV	M	Lumbricalis I—I
OPP POLL	M	Opponens pollicis
OPP V	M	Opponens digiti
PB	M	Palmaris brevis
RA		Ramus articularis
MP joint		Metacarpo phalangeal
CMC joint		Carpo metacarpal joir
PIP joint		Proximal interphalang joint
DIP joint		Distal interphalangeal
IP joint		Interphalangeal joint

ABBREVIATIONS IN TABLES

ABD II	Radial abduction of index finger
ABD V	Ulnar abduction of little finger
ADD POLL	Palmar adduction of thumb
ADD II i	Adduction in second interspace
ADD IV i	Adduction in fourth interspace
PINCH	Pinching grip

Part II Anatomy

Chapter I Normal and anomalous pattern of innervation of the ulnar nerve

The hand is supplied mainly by 3 nerves: the radial, the median and the ulnar nerves. The radial nerve originates from the fasciculus dorsalis (C5—ThI). The median nerve: radix lateralis from fasciculus lateralis (C5—C7) and radix medialis from fasciculus medialis (C8—ThI). The ulnar nerve also stems from the fasciculus medialis (C7—ThI). According to Linell (1921) and Foerster (1929) the flexor carpi ulnaris muscle is innervated to a certain extent by fibres from segment C7.

For practical reasons 4 zones of the ulnar nerve were distinguished in this investigation (Fig. 1 and Table 1). The *first zone* comprises the proximal part of the ulnar nerve extending from the brachial plexus to the first branch of the nerve inclusive, viz. the ramus articularis to the elbow. The *second zone* extends from this level to the level just distal to the origin of the ramus dorsalis manus of the ulnar nerve in the distal part of the lower arm. The *third zone* extends from this point to the level of the hamular process to and including the origin of the ramus profundus with branches to the 3 hypothenar muscles: abductor digiti quinti, opponens digiti quinti and flexor brevis digiti quinti. The *fourth zone* comprises the end of the ulnar nerve.

ZONE I. NORMAL PATTERN OF INNERVATION

The ulnar nerve is situated in the caudal part of the fasciculus medialis in the infra-clavicular part of the brachial plexus. This segment of the nerve runs on the ulnar side of the axillary artery. At this level the nerve lies close to the nervi cutanei brachii et antebrachii ulnares and radix medialis of the median nerve. Dorsal to the septum intermusculare brachii the nerve runs in distal direction without sending off any branches down towards the sulcus nervi ulnaris on the dorsal aspect of the elbow. Here the nerve follows the arteria collateralis ulnaris proximalis. Somewhat proximal to this level the ulnar nerve gives off its first branches, namely the rami articulares to the elbow (see Table 1).

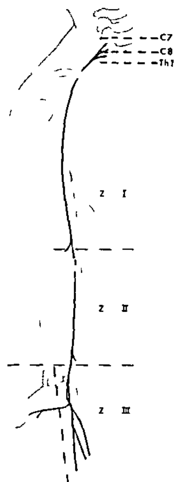


Fig. 1. Zones of right ulnar nerve

ZONE I. ANOMALOUS PATTERN OF INNERVATION

According to Linell (1921) the ulnar nerve rarely gives off any branch above the elbow. However, in a series of 20 dissected ulnar nerves Sunderland & Hughes (1946) found a branch to the flexor carpi ulnaris which originated at the level of the epicondyle in one case and in another a branch that ran to the aforementioned muscle 4 cm proximal to the epicondyle. The level of the origin of the rami articulares also varies, but according to Sunderland (1945) it never arises at a level more than 7 mm above the epicondylus ulnaris humeri.

Table 1 Right ulnar nerve — zones and branches

Zone	No	Musc branches	Sens branches	Other branches
Zone I	1		RA elbow joint	
Zone II	2		RA elbow joint	
	3	FCU		
	4		RA elbow joint	
	5	FCU		
	6	FDP IV and V		
	7	FDP IV and V		
	8	FCU		
	9			Nerve of *Henle*
	10		R palmaris	
	11		R dors manus	
Zone III	12			Nerve of *Henle*
	13		R Superfic. from Dig 1/2 IV and V	
	14	PB		
	15	R. Profundus		
	16	ABD V		
	17	FD V B		
	18	OPP V		
Zone IV	19			Nerve of *Henle*
	20	L IV		
	21	IOV+D 4th space		
	22	IOV+D 3rd space		
	23	L III		
	24		RA carpal joints	
	25	IOV+D 2d space		
	26	ADD POLL oblique portion		
	27	ADD POLL transv portion		
	28	IOD I		
	29	FPB deep portion		
	30			(*Riche Cannieu* anastomosis)

ZONE II NORMAL PATTERN OF INNERVATION

In zone I the nerve is relatively superficial and shiftable but in zone II it dips into the sulcus nervi ulnaris and further distally between the two heads of origin of the flexor carpi ulnaris and here down as in an osseofibrous tunnel The floor of the tunnel consists of the medial collateral ligament of the elbow joint its roof of fibrous tissue forming an aponeurosis filling the triangular gap between the two heads of origin of the flexor carpi ulnaris This tunnel has been called the cubital tunnel (Feindel and Stratford

1958) Here the ulnar nerve sends off its first motor branch the one innervating the flexor carpi ulnaris According to Sunderland and Hughes (1946) the origin of the motor branches to the flexor carpi ulnaris varies widely As mentioned in a study on 20 cadavers the present writers found the branch to the flexor carpi ulnaris to originate at the level of the epicondyle in one case and 4 cm proximal to the epicondyle in another In both cases branches ran to the flexor carpi ulnaris also distally No branches to the flexor carpi ulnaris were seen at or above the epicondyle in any of the remaining 18 cases This is in agreement with Linell s (1921) observation that the ulnar nerve rarely gives off branches to muscles above the elbow As a rule the branches running to the flexor carpi ulnaris and flexor digitorum profundus IV—V originate at separate levels of the ulnar nerve but sometimes they are given off in the form of a single branch, which then divides to supply these muscles (Sunderland and Hughes 1946) According to these authors the first motor branch often supplies the musculus flexor carpi ulnaris but in their material (20 cadavers) they sometimes also found a first branch supplying the flexor digitorum profundus IV—V muscle They found the last motor branch in the lower arm to supply the musculus flexor carpi ulnaris in 9 cases the flexor digitorum profundus in 6 and as a bifurcated branch in the remaining 5 In 19 of their 20 cases they found multiple branches to leave the nerve and to supply the musculus flexor carpi ulnaris

In the distal part of the lower arm the arteria ulnaris is on the radial side of the nerve There the ulnar nerve gives off fine branches to this artery Kaplan (1965) calls this nerve Henle s nerve Henle (1868) described these nerves as chiefly vasomotor Sometimes in association with one of these small Henle nerves sometimes as an independent branch a fine nerve is sent off from the ulnar nerve at a level somewhat proximal to the middle of the forearm namely the ramus palmaris which supplies the skin in the ulnar part of the proximal carpus and the palm of the hand The ulnar nerve so far sandwiched between the musculature of the flexor carpi ulnaris and digitorum profundus IV—V then runs distally along and beneath the tendon of the flexor carpi ulnaris and gives off its last branch in zone II namely the ramus dorsalis manus This branch originates at the transition between the middle and distal third of the forearm and then runs between the ulna and the tendon of the flexor carpi ulnaris in distal dorsal direction This sensory branch runs somewhat proximal to the caput ulnae through the fascia and then divides subcutaneously into its end branches *supplying with certain variations,* the ulnar distal parts of the dorsal part of the hand and the dorsal parts of the 5th and 4th fingers and the ulnar part of the 3rd finger (Villiger Ludwig 1946 von Lantz Wachsmuth 1959)

Turner (1874) described an isolated branch arising at roughly the middle level in the forearm from the trunk of the ulnar nerve and running as a fine nerve on the volar side of the volar carpal ligament out to the ulnar part of the 4th finger The ramus dorsalis manus sometimes originates at different levels of the lower arm The variation in the innervation of the flexor carpi ulnaris and the flexor profundus IV—V has been described (*vide supra*) by Sunderland and Hughes (1946)

The main anomaly in zone II is however the occasional anastomosis between the median and ulnar nerves This anomaly was apparently first described by the Swedish anatomist R Martin who (1763) in his *Tal om Nervers allmanna Egenskaper i Mannislans kropp* where he wrote (paragraph 179 on the median nerve) that en gren som stundom gar under pronator teres att anastomosera med cubiteo N B ar denna stor fins ofta ej nagon Nervus anastomoticus i vola manus som gor arcum volarem Cubiteo was the term used at that time to designate the ulnar nerve In paragraph 181 is to be read on Nervus cubitalis s ulnaris 4 0 ofta en anastomose gren med mediano dock ej bestandigt

According to Gruber (1870) the anatomical literature from Vesalius and Vieussens (1690) to Monro (1763) does not mention anything about an anastomosis between the median and the ulnar nerve in the forearm With reference to Martin (1763) Gruber then dissected 125 cadavers and thereby found an anastomosis in 38 of 250 arms (15 2 %) The anastomosis was bilaterally in 10 cases (8 males and 2 females) It was thus unilateral in 18 and was right sided in 4 (males) and left sided in the remaining 14 (12 males and 2 females)

Hirasawa (1931) of Japan found the anastomosis in 10 5 % of a similar material consisting of 124 arms As in Gruber s series the anastomosis was more common on the left side

According to Hirasawa (1931) Ssokolow (1925) demonstrated this anastomosis in 44 % of 55 arms in Russians and Curtis (1886) in 30 7 % (19 of 62 arms) in a French series

Borchhardt and Wjasmenski (1917) found the anastomosis in 2 of 4 cases in which the median nerve was dissected and slit up

It might be convenient at this stage to give a brief description of the phylogenesis of this Martin-Gruber anastomosis to facilitate the understanding of the character of the anastomosis

A thorough analysis of the phylogenesis of the hand has been published by Bunnell (1956) Bunnell shows that the intrinsic muscles of the hand can be traced back through the animal series to the early fish when there was no arm but only a pectoral fin from which the hand later developed

Thus phylogenetically the hand preceded the arm which developed later and from higher cervical segments (The intrinsic muscles of the hand are thus primordial) The intrinsic muscles in Homo are still supplied by the two lowest nerves in the brachial plexus and this applies to both the ulnar and median nerves (Wood Jones 1949)

This is not in agreement with Rauber Kopsch (1940) and Villiger Ludwig (1946) who state that *inter alia* opponens pollicis is innervated by C6—C7 In further support of the intrinsic muscles of the hand being supplied by the two lower segments of the brachial plexus reference may be made to the clinical picture of Klumpke s paralysis which affects the lower part of the brachial plexus The small muscles of the hand there are paralysed both those innervarted by the ulnar nerve and those innervated by the median nerve

It is also interesting to note that in the early stages of evolution (in amphibiae reptiles birds see Foerster 1929) the three flexor group nerves *i e* musculocutaneous the median and the ulnar nerve were originally united in a common ventral trunk Moreover in several types of monkeys the anastomosis between the median nerve and the ulnar nerve is an invariable phenomenon (Hepburn 1892)

Ranschburg (1917) wonders whether this anastomosis is motor sensory or mixed He refers to Curtis (1886) who describes 3 forms of this anastomosis namely the straight one which was said to be of purely sensory nature the looped one with its convexity distally and giving off muscular branches and finally the mixed one which is regarded as a combination between the first two forms and which also gives off motor branches Ranschburg dissected 12 forearms and found an anastomosis between the median and ulnar nerves in four 2 on the right and 2 on the left These 4 cases were said to represent two essentially different morphologic types As the first type Ranschburg found a simple anastomosis between the ulnar and median nerves and according to him it carried sensory fibres from the ulnar to the median nerve The second type was fan shaped or Y shaped and was a true motor anastomosis from the median to the ulnar nerve and thus *formed part of the deep ulnar nerve Borchhardt and Wjasmenski (1917)* who split up 2 preparations of the median nerve found an anastomosis with the ulnar nerve and in their opinion this anastomosis went down to the motor branch of the ulnar nerve

All of the above mentioned authors demonstrated the anastomosis in cadavers The clinical literature contains only scanty reports on the occurrence of this anastomosis Thus Remak (1874) described a case of ulnar nerve injury in the upper arm with paralysis of the flexor carpi ulnaris but without substantial impairment of function of the other muscles normally innervated by fibers of the ulnar nerve Electrical stimulation of the

ulnar nerve above the injury produced no response of the flexor carpi ulnaris muscle but stimulation below the injury produced a response of those muscles normally innervated by the ulnar nerve More recent clinical literature contains only single references to this Martin-Gruber anastomosis (Goldman 1906 Cliffton 1948 Rowntree 1949 Brash 1955) In Surgery of the Hand (Bunnell 1956) only little space is given to anastomoses between the median and the ulnar nerve

Thus each author reports only a few cases i e numbers too small to permit statistical analysis of the frequency of the anomaly

Recently Goldner and Jones (1966) in a series of 25 patients with nerve injuries showed some cases with a true Martin Gruber anastomosis

ZONE III NORMAL PATTERN OF INNERVATION

The level of the origin of the opponens digiti quinti and flexor brevis digiti quinti i e after the nerve had passed hamulus ossis hamati was chosen as the lower limit of zone III All hypothenar muscles thus are innervated by the nerve in this zone The reason for this level was also to incorporate the so called Guyon s loge (Guyon 1861) in this zone In the proximal part of this zone III the ulnar nerve divides into the ramus superficialis and the ramus profundus The ramus superficialis lies more superficial and on the radial side of the ramus profundus The nerve extends with its two branches volar to the ligamentum carpi transversum and there the pisiform bone lies on the ulnar side There the 2 branches of the nerve are covered by the palmaris brevis muscle and a thin layer of fascia the volar carpal ligament The nerve lies in Guyon s loge (which Barthold (1960) calls the ulnar canalis carpi) on a floor formed by ligamentum piso-hamatum The ramus superficialis gives off a motor branch (branches) to the palmaris brevis which may however be innervated by branches from the ramus profundus After first running radially to the deep branch the superficial branch courses in a distal direction and then divides into the nervus digitalis ulnaris V the nervus digitalis volaris radialis V and the ulnaris IV It also probably invariably gives off a branch to the nervus digitalis volaris communis dig III from the median nerve The superficial branch thus supplies the entire volar surface of the 5th finger and the ulnar volar part of the 4th finger Branches sometimes extend up to the dorsal surface of the distal phalanx of the 5th finger and ulnar half of the intermediate and distal phalanx of the 4th finger (Villiger Ludwig (1946)

According to Sunderland and Hughes (1946) the pattern of the motoric innervation of the deep ulnar branch here sometimes varies in that a common branch divides to form future branches of the flexor brevis opponens dig V and to both volar and dorsal interossei to the 4th interspace As a

rule however branches to the abductor brevis V are given off before those branches supplying the flexor brevis V and opponens V

After the nerve has given off motor branches to these 3 hypothenar muscles it dips and loops around the ulnar aspect of the hook of the hamate (Boyes 1964) in radial distal direction and passes into zone IV There the nerve is covered by the origin of opponens digiti quinti and flexor brevis digiti quinti

ZONE III ANOMALOUS PATTERN OF INNERVATION

In 1963 Kaplan described a variation of the ramus dorsalis manus with an unusual distribution enclosing the pisiform bone A similar variant called an auto anastomosis was described in 1938 by Hirschlaff Hjortsjo

ZONE IV NORMAL PATTERN OF INNERVATION

After the deep motor branch of the ulnar nerve has left the tunnel limited by the distal part of the hamatum and the origin of the opponens V and flexor brevis V the nerve continues in radial direction where it lies deep under the long flexor tendons in the hand It gives off motor branches to the 4th lumbrial and sometimes also a Henle s nerve to the deep palmar branch of the ulnar artery which it accompanies on its path radial wards This arterial branch belongs to the arcus volaris profundus In the order given motor branches then extends to interossei in the 4th and 3rd interspaces and to the 3rd lumbrical after which it receives some articular branches from the carpo metacarpal inter metacarpal and metacarpo phalangeal joints more or less radially in the hand (v Lanz Wachsmuth 1959) The interossei in the 2nd interspace are then supplied by the nerve which then divides into branches running to oblique and transverse parts of the adductor pollicis and to branches of the interos eus in the first interspace Before this the ramus profundus of the ulnar nerve runs through a small arcade which is situated in the transition between the transverse and oblique head of the adductor pollicis The nerve supplies the adductor muscles with fibers entering the dorsal side of this muscle The nerves to the interosseous dorsalis I enter this muscle from the volar aspect The nerve is thereby sandwiched between the adductor pollicis and inter osseus dorsalis I Sunderland and Hughes (1946) found the adductor pollicis to be supplied before the 1st dorsal interosseus in 10 of 20 preparations at the same distance in 7 of 20 preparations and distal to the first dorsal interosseus in 1 case The 1st dorsal interosseus might according to these authors thereby be the last of the muscles innervated by the ulnar nerve They did not however extend their investigation to include innervation

of the deep head of the flexor pollicis brevis The deep part of the flexor pollicis brevis is innervated not only by the median nerve but also by the ulnar nerve in varying frequency (Brooks 1886 Spourgitis 1895 Cannieu 1896 1897 Riche 1897 Foerster 1929 Highet 1943 Murphey Kirklin and Finlayson 1946 Wood Jones 1949)

ZONE IV ANOMALOUS PATTERN OF INNERVATION

The anatomical and clinical literature dealing with the anomalous pattern of innervation of this zone is fairly abundant and contradictory The anomalies fall largely into 5 different types

1 Double innervation of interosseus dorsalis I
2 Double innervation of lumbricals
3 Thenar muscles innervated entirely or partly by the ulnar nerve
4 Anastomosis between deep ulnar branches and motor branches of the median nerve in the radial part of the palm of the hand
5 Hypothenar muscles innervated entirely or partly by the median nerve

Some authors studied these patterns in cadavers other by careful analysis of muscle function after complete or partial nerve injury

Double innervation of interosseus dorsalis I

Double innervation of the interosseus dorsalis I was demonstrated by Murphey Kirklin and Finlayson (1946) in 4 out of 698 patients with ulnar injury In these 4 cases then the interosseus dorsalis I was either innervated only by the median nerve or by both the median nerve and the ulnar nerve In his investigation of 124 patients with ulnar injuries Rowntree (1949) found double innervation of the interosseus dorsalis I in 2 and possibly in 4 Double innervation of interosseus dorsalis I therefore appears to be relatively rare

Double innervation of lumbricals

Brooks (1887) described double innervation of lumbricals Double innervation of lumbricalis I by both the median nerve and the ulnar nerve could not be demonstrated in any of his 21 cases but such double innervation of the 2nd lumbrical was found in 1 case of the 3rd lumbrical in 2 and of the 4th lumbrical in 1 of his 21 cases Riche (1897) also found double innervation of certain lumbricals by the median and ulnar nerves

Thenar muscles entirely or partly innervated by the ulnar nerve

It would appear that Brooks (1886) was one of the first to demonstrate double innervation of the flexor pollicis brevis muscle by both the ulnar and

the median nerves According to Rowntree (1949) the flexor pollicis brevis is innervated by more than one nerve in more than 50 % of cases of injury to the ulnar and median nerve

Foerster (1929) reported cases in which the ulnar nerve had innervated all thenar muscles in a case of median injury but he made no attempt to ascertain whether the muscles were innervated by both the median and the ulnar nerves Cliffton (1948) studied 250 ulnar injuries and 150 median injuries and found the function of the opponens pollicis flexor pollicis and abductor pollicis brevis to be preserved in only 1 case of complete median injury In this case these muscles were innervated by the ulnar nerve

That the opponens pollicis can be innervated by the ulnar nerve is known But it is surely rare and Murphey Kirklin and Finlayson (1946), who studied 551 injuries of the median nerve found that the opponens pollicis was innervated by the ulnar nerve in only 1 case

Anastomosis between ramus profundus of the ulnar nerve and motor branch of median nerve in the palm of the hand

Such anastomoses have been demonstrated by several authors who have wondered whether the anastomoses between the ramus profundus of the ulnar nerve and motor branch of the median nerve are sensory motor or mixed Turner (1874) believed that the communication in the hand passed from the ulnar to the median nerve Foerster (1929) who founded his opinion on a large number of war injuries believed the anastomosis to be of motor type Gehwolf (1921) assumed the anastomosis to be of sensory type Cannieu (1897) found the anastomosis in 3 out of 23 cadavers Ranschburg (1917) found no such anastomosis in 12 cadavers studied Riche (1897) reported 3 types of anastomosis between the ramus profundus of the ulnar nerve and motor branches of the median nerve The first was a connection across the tendon of the flexor pollicis longus between the motor median nerve branch that run to the superficial head of the flexor pollicis brevis and the ulnar branch running to the deep head of the flexor pollicis brevis Another type is the anastomosis between the median nerve and the deep branch of the ulnar nerve across the first lumbrical The last type was discovered by Riche (1897) and is a branch from the median nerve extending to the ulnar nerve and piercing the substance of the adductor pollicis and anastomosing in that muscle with the motor branch given off thereby the ramus profundus

Judging from the literature then this anastomosis in the hand is not uncommon In the literature it has been called the Riche Cannieu anastomosis Opinions differ on the nature of the anastomosis some regard its nature as obscure some think it to be of motor type while others believe

it to be of sensory type A search of the literature failed to reveal any systematic investigation of the nature of the anastomosis

Hypothenar muscles entirely or partly innervated by the median nerve

According to the literature the hypothenar muscles are rarely innervated by branches of the median nerve One case has been published by Murphey Kirklin and Finlayson (1946) and a few by Gassel (1964) and Marinacci (1964)

SUMMARY

The normal anatomy of the ulnar nerve is reviewed For practical reasons 4 zones of the nerve were distinguished Various forms of anomalous innervation are presented The most important ones—the Martin Gruber and Riche Cannieu anastomoses—are described in detail

Chapter II Author's dissection of the ulnar nerve

To form an opinion of the anatomy of the ulnar nerve and muscles governed by the nerve 15 fresh post mortem specimens (right hand) and one amputated (left hand) were studied The specimens are numbered 1—16 In 9 of them interest was focused particularly on the nerve The dissection comprised zones II III and IV

In zone II (Fig 2) well defined Henle s nerves to the ulnar artery were seen (Henle 1868 Kaplan 1965) Multiple branches to the flexor carpi ulnaris described previously by Sunderland (1946) for example were also found In one preparation (No 13) two branches were seen to supply the flexor digitorum profundus IV—V

In zones III and IV the findings were those largely expected from the standard anatomic literature Some Henle s nerves could be demonstrated in zone III (Fig 3) In 2 of 3 specially prepared specimens (Nos 14 and 15 see Fig 3) the palmaris brevis musculature was innervated by the superficial ulnar branch in the 3rd preparation (No 2) this muscle was innervated by the deep ulnar branch Superficial sensible anastomosis with the median innervated digital nerve to the 3rd interspace could be demonstrated in all the cases studied The deep ulnar nerve in 1 (No 2) of the 3 specially examined preparations sent a branch to the interosseus dorsalis I earlier and to adductor pollicis later and the last muscle innervated by the ulnaris in that preparation was the deep head of the flexor pollicis brevis In preparation No 3 double innervation of the adductor pollicis was strongly suspected because the nerve fibres to that muscle came from both the deep ulnar nerve and the motor branch of the median nerve This resembles the third type of anastomosis described by Riche (1897) In preparation No 8 the interosseus dorsalis I was the last muscle innervated by the deep ulnar branch In preparations 7 8 and 9 a search was made for anastomoses between the deep ulnar nerve and the motor branch of the median nerve Such anastomoses were found in all 3 consecutive cases studied (Figs 3 and 4) These dissections thus verified what most other authors have found namely an ansa or anastomosis between the deep ulnar nerve in the palm and motor branch of the median nerve (Turner 1874 Riche 1897 Cannieu 1897 Frohse and Frankel 1908 Ranschburg 1917

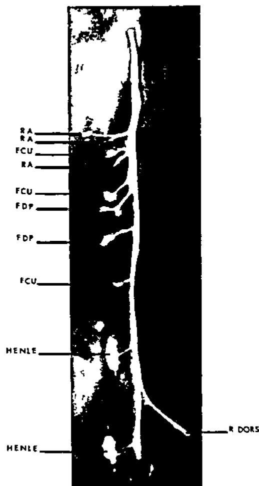


Fig 2 Right ulnar nerve zone II Preparation number 13 in present series

Gehwolf 1921 Foerster 1929) It is this anastomosis that is known in the literature as the Riche Cannieu anastomosis The question whether this connection is rather constant must for the time being left unanswered because the material was too small

In 1 case (No 15 Fig 3) the deep ulnar branch was found to innervate lumbricalis II a finding made by Brooks (1887) in 1 of his 21 dissected hands Whether the lumbricalis II in this case was doubly innervated also by the median nerve was not investigated further


4
5
6
9
g
f
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a
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11
FPL

Fig 3 Right ulnar nerve zone III—IV Reproduction composed of two preparations (Nos 15 and 9)

Key to symbols

1	N Ulnaris	a	PB
2	R Superficialis N Ulnaris	b	ABD V
3	R Profundus N Ulnaris	c	OPP V
4	Digital nerve from ulnar side of little finger	d	FD V B
5	Digital nerve from radial side of little finger	e	IOV II
6	Digital nerve from ulnar side of ring finger	f	IOD III and L III
7	N *Henle's nerve to a digital artery* in the palm	g	L II
8	R communicans to median nerve in the palm	h	IOV I
9	Digital nerve from radial side of ring finger from median nerve	i	IOD I
10	Riche Cannieu anastomosis betwen deep ulnar nerve and motor branch of the median nerve see also fig 4	j	*ADD POLL*
11	N Medianus	k	FPB
		x	Borderline between two preparations Nos 15 and 9
		z	Borderline between zone III and IV



Fig 4 Riche Cannieu anastomosis Preparation number 9 Deep ulnar nerve to the left median nerve to the right

SUMMARY

The ulnar nerve was dissected in nine specimens within zones II—IV The findings were those largely expected from the standard anatomic literature In three preparations the so called Riche Cannieu anastomosis was found In one case the deep ulnar branch was found to innervate the second lumbrical muscle

Chapter III On muscles and tendons of the thumb, index finger and little finger

In the investigation of the function of a muscle it is necessary to consider not only its origin insertion amplitude and innervation pattern but also the course of the muscle and its tendons relative to the axes of pertinent joints (Landsmeer 1955 1963 Hjortsjo 1959 1964)

The muscles acting upon the hand fall into 2 groups extrinsic and intrinsic An intrinsic muscle has both its origin and insertion in the hand while an extrinsic muscle is one which although it acts upon the hand has its origin in the arm This classification of the muscles is less satisfactory from a functional point of view because practically every movement of the hand is the result of an intricate interplay between extrinsic and intrinsic muscles From a descriptive point of view however it is useful

INTRINSIC MUSCLES OF THE THUMB

The thenar group consists of the abductor pollicis brevis opponens pollicis flexor pollicis brevis and adductor pollicis

Abductor pollicis brevis

This muscle is the most dorsoradial and most superficial of the muscles representing the thenar profile The muscle which is well defined originates mainly from the ligamentum carpi transversum and from the eminentia carpi radialis The tendon of the muscle is inserted on a tuberosity on the radial side of the base of the proximal phalanx of the thumb According to v Lanz Wachsmuth (1959) the muscle is also inserted on the radial sesamoid bone an assertion denied by Stener (1962) As a rule fibres from the superficial part of the muscle continue up through a superficial aponeurosis to the dorsum of the 1st phalanx of the thumb where the aponeurosis unites with the tendon of the extensor pollicis longus as an insertion on the radial side of the terminal phalanx This aponeurosis may be called the abductor aponeurosis in analogy with the adductor aponeurosis radiating from the ulnar side (Mondry 1940 Stener 1962) Sometimes an extra tendon from the abductor pollicis longus enters the abductor pollicis

brevis muscle and this tendon may also lie superficially on the abductor pollicis brevis and unite with the superficial abductor aponeurosis

Opponens pollicis

The origin of this muscle is situated immediately beneath the origin of the abductor pollicis brevis The muscle originates from the ligamentum carpi transversum from eminentia carpi radialis and from the joint capsule in the carpo metacarpal joint I The muscle runs obliquely in distoradial direction and is fixed osseously along the lateral border of the first meta carpal and therefore represents the only thenar muscle that is attached to this bone The other 3 thenar muscles are attached distally to the first metacarpal

Flexor pollicis brevis

Opinions differ on this muscle According to Wood Jones (1949) the flexor pollicis brevis has not two heads but four

1 The superficial head gaining origin from the ligamentum carpi trans versum is attached to the radial sesamoid bone The muscle runs on the volar and radial side of the tendon of the flexor pollicis longus According to Flemming (1887) this is the only head that deserves the name flexor pollicis brevis
2 The deep head takes origin from the multangulum majus and capitatum The belly of the muscle runs on the dorsal side of the tendon of the flexor pollicis loungus and this part of the muscle is inserted also on the radial sesamoid bone
3 4 Wood Jones mentions 2 other muscle bundles attached to the ulnar sesamoid bone One of them runs along the ulnar border of the first metacarpal and likewise originates proximally and ulnarly from this bone According to Wood Jones (1949) this is what most British anatomists call the inner deep head of the flexor pollicis brevis Other anatomists call this muscle the first palmar interosseus Wood Jones refers to this muscle as Henle s interosseus primus volaris

Kaplan (1965) found that the flexor pollicis brevis was inserted on the radial sesamoid bone and on the fibrocartilago volaris and partly on a radial tuberosity on the base of the basal phalanx of the thumb and finally with an expansion up in the long extensor tendon of the thumb In a special study of the flexor pollicis brevis Day and Napier (1961) found the deep head to be missing in 3 of 65 hands dissected

However this difference in conception of the flexor pollicis brevis can be cleared up if it be assumed that the muscles inserted on the radial

sesamoid bone are called flexor pollicis brevis and those inserted on the ulnar sesamoid bone adductor pollicis (Frohse Frankel 1908 Wood Jones 1949 and Stener 1962)

Adductor pollicis

This muscle consists of at least 2 well defined muscle bellies called the ad ductor pollicis transversus and the adductor pollicis obliquus The trans verse belly springs from the major part of the 3rd metacarpal roughly from the midline of its volar surface This transverse belly runs radialwards covering the 2nd metacarpal the 1st volar and the 1st dorsal interosseus to terminate in 3 insertions on the ulnar side of the thumb The oblique belly arises from the carpus in the region of capitatum and multangulum minus and from the base of the 3rd metacarpal Between the transverse and the oblique parts there is a small arcade through which run the deep branch of the ulnar nerve and the arcus volaris profundus (ramus volaris profundus of the arteria radialis and the arteria ulnaris) The oblique portion is inserted on the ulnar sesamoid bone According to some authors parts of the adductor pollicis are inserted on the radial sesamoid of the thumb (Wood Jones 1949) Provided however that the muscle bundles inserted on the radial sesamoid are called flexor pollicis brevis and those inserted on the ulnar sesamoid adductor pollicis there need no longer be any confusion (Frohse Frankel 1908 Wood Jones 1949 and Stener 1962) According to Rauber Kopsch (1940) and v Lanz Wachsmuth (1959) the adductor pollicis is inserted only on the ulnar sesamoid of the thumb ac cording to others (Wood Jones 1949) on the ulnar sesamoid and the base of the first phalanx of the thumb Several authors have demonstrated the aponeurosis which extends from the adductor pollicis to the tendon of the extensor pollicis longus (Mondry 1940 Strandell 1959 Stener 1962 and others) As early as 1867 Duchenne pointed out that fibres extend to the tendon of the extensor pollicis longus This was also mentioned by Foerster (1937) The adductor muscle inserts on a tuberosity on the first phalanx of the thumb According to Frohse Fränkel (1908) this is the tuberosity which Poirier called tuberosite interne et superieure de la premiere pha lange du pouce

EXTRINSIC MUSCLES OF THE THUMB

These muscles consists of the extensor pollicis longus extensor pollicis brevis abductor pollicis longus and flexor pollicis longus

Extensor pollicis longus

The extensor pollicis longus gains origin from the extensor surface of the ulna immediately proximal to the origin of the extensor indicis proprius It

also originates partly from the membrana interossea. The muscle is bipennate and merges in a tendon on the dorsal side of the muscle, somewhat proximal to the radio-carpal joint. It is Lister's tuberosity on the dorsal side of the distal radius which then causes the tendon to assume a radial direction. The extensor pollicis longus runs in the 3rd compartment of the ligamentum carpi dorsale in distal direction towards the thumb where it obliquely crosses the tendons to the extensor carpi radialis longus and brevis and then courses to the ulnar side of the dorsal surface of the thumb finally to be inserted on the base of the terminal phalanx of the thumb. The extensor pollicis longus lies in the 3rd compartment firmly anchored but relatively movable from side to side from the level of the multangulum majus right up to the point where the tendon meets fibers from the adductor aponeurosis (Stener 1962) and the "abductor aponeurosis" at the level of the 1st metacarpo-phalangeal joint. But, even at this level the tendon can be displaced to a certain extent laterally. The adductor aponeurosis and "abductor aponeurosis" together also called the hood can be moved a few millimetres in distal proximal direction (Bunnell 1956). On its radial side the extensor pollicis longus tendon is accompanied for a short distance by the extensor pollicis brevis tendon.

Extensor pollicis brevis

This muscle originates from the membrana interossea and from the extensor aspect of radius below the middle of the latter and lies beneath the muscle bundles of the extensor pollicis longus and abductor pollicis longus. Its tendon forms at the level of the distal part of the radius and runs together though sometimes separated by a sheath with the abductor pollicis longus in the first compartment of ligamentum carpi dorsale. The tendon runs along the dorsal aspect of the 1st metacarpal and is usually inserted on the base of the first phalanx of the thumb. Variations have been described in the literature. Thus Stein (1951) for example reported a double extensor pollicis brevis tendon in 4 % of 84 dissected hands when the extensor ran in the same sheath as the abductor pollicis longus. The extensor pollicis brevis tendon rarely appears to be in contact with the abductor aponeurosis but to pass beneath the aponeurosis on its way to its insertion on the first phalanx. In one case Kaplan (1965) found that the tendon of the extensor pollicis brevis continued along the extensor pollicis longus tendon on both the first phalanx and the distal phalanx of the thumb where it was inserted together with but radially to the extensor pollicis longus tendon. Strandell (1955) found that the tendon of the extensor pollicis brevis ran along the *radial* part of the 1st metacarpal. The first compartment in which the extensor pollicis brevis runs, serves also as an

annular ligament of the abductor pollicis longus tendon — tendons This compartment which in Quervain's disease (de Quervain 1912 Wiberg 1941) is to be separated longitudinally is sometimes divided into 2 compartments Lipscomb (1951) stresses the necessity of unroofing both compartments in such cases

Abductor pollicis longus

The abductor pollicis longus originates from the extensor surface of the ulna proximally to the origin of the extensor pollicis longus and distally to the insertion of the supinator The muscle gains origin also from the membrana interossea and from part of the radius The belly of the muscle then runs disto-radially and its tendon courses together with the tendon of the extensor pollicis brevis through the 1st compartment of the ligamentum carpi dorsale (see above) The tendon or tendons of abductor pollicis longus have often more than one insertion In most cases the tendon is inserted on the base of the 1st metacarpal Thus Fenton and Lapidus (1953) who dissected 54 wrists arrived at the conclusion that at least one tendon of the abductor pollicis longus was always inserted on the base of the 1st metacarpal In the variant forms *i e* with extra tendons the latter were sometimes inserted on the soft tissue sometimes on bony structures of the wrist Of 84 dissected hands Stein (1951) found that in 68 % the abductor pollicis longus tendon was double when it passed into the same sheath as the extensor pollicis brevis as it most often did Occasionally a tendon of the abductor pollicis longus blended with the muscle and the fascia of the abductor pollicis brevis and passed out through its tendon distally

Flexor pollicis longus

This muscle springs partly from the volar surface of the radius distal to the insertion of the supinator and partly from neighbouring parts of membrana interossea The muscle which is unipennate merges into a tendon on the ulnar distal side of the muscle belly After the tendon has passed through the canalis carpi it lies between the superficial and deep head of the flexor pollicis brevis and after it has passed through a relatively narrow tendon sheath it is inserted on the base of the volar surface of the terminal phalanx of the thumb This tendon unlike that of the extensor pollicis longus can thereby move only to a small extent laterally The flexor pollicis longus is the only muscle that can flex the terminal phalanx of the thumb while most of the intrinsic muscles of the thumb (adductor pollicis flexor pollicis brevis and abductor pollicis brevis) flex the basal phalanx of the thumb in the metacarpo phalangeal joint

INTRINSIC MUSCLES OF THE INDEX FINGER

The index finger has 3 intrinsic muscles, the interosseus dorsalis I interosseus volaris I and the 1st lumbrical Landsmeer (1955 and 1963) focused special attention on the anatomy and function of these muscles He thought that Albinus (1734) should be regarded as the first to have demonstrated the differences between the dorsal and volar interossei and that he should also be regarded as one of the earliest to report the observation that the first dorsal interosseus is inserted osseously on the radial part of the base of the index finger Albinus therefore called this muscle the abductor indicis The 1st dorsal interosseus originates from both the 1st and 2nd metacarpal and must be regarded as the strongest of all the 7 interossei of the hand Its tendon runs on the volar side of the radio ulnar axis of movement in the 2nd metacarpo phalangeal joint (Landsmeer 1955) The 1st dorsal interosseus consists of two parts The dorsal component is attached according to Landsmeer (1955) osseously to a tuberosity on the radial aspect of the first phalanx The volar component runs a more varying course in distal direction He found that fibers from the first dorsal interosseus were always fixed osseously and that only few extended up into the dorsal aponeurosis or into the hood

The other muscle of the index finger that extends up into the radial hood is the 1st lumbrical This muscle arises from the radial aspect of the tendon of the flexor profundus of the index finger and separated from the adductor it runs distally out along the radial side of the index finger Its tendon is attached to the dorsal aponeurosis

The 1st volar interosseus belongs to the homogeneous group of 3 muscles none of which show any osseous attachment (Landsmeer 1955) Its tendon thus runs in dorsal direction up as the ulnar wing of the dorsal aponeurosis The major part of the tendon runs on the volar side of the radio ulnar axis of movement of the metacarpo phalangeal joint (Landsmeer 1955)

EXTRINSIC MUSCLES OF THE INDEX FINGER

These muscles consist of 2 extensors and 2 flexors the extensor indicis proprius extensor digitorum communis II flexor digitorum sublimis and flexor digitorum profundus II

Extensor indicis proprius

This muscle originates from the extensor surface of the ulna and from the membrana interossea The muscle which belongs to the deeper layer of the extensors merges with its tendon at the level of the wrist and runs in the 4th compartment of the ligamentum carpi dorsale to reach the index finger

on the ulnar side of the extensor digitorum communis with whose terminal tendons it unites In this way it reaches the terminal phalanx of the index finger and here merges with the extensor digitorum communis II (see below) The action of the extensor indicis proprius is fairly independent (Wood Jones 1949) while in ulnar paralysis the index finger can still be adducted against the third finger with the help of this tendon This therefore indicates that the extensor indicis proprius tendon lies on the ulnar side of the dorso-volar axis in the 2nd metacarpo-phalangeal joint

Extensor digitorum communis II

This muscle together with other extensors of the superficial group arises from the radial epicondyle of the humerus In the common extensor (digitorum communis II—V) mass a relatively distinct muscle can be recognized for the index finger the extensor digitorum communis II The muscle passes into the tendon somewhat proximally to the radiocarpal joint and runs in the 4th compartment of the ligamentum carpi dorsale When the tendon reaches the 2nd metacarpo phalangeal joint it spreads in both directions to form the hood with transverse fibres running in volar direction This hood can be displaced a few millimetres in proximal distal direction (Bunnell 1956) Oblique fibres extend up into the extensor aponeurosis distally to the metacarpo phalangeal joint on the radial side the 1st lumbrical and the 1st dorsal interosseus on the ulnar side the 1st volar interrosseus

A deeper part of the extensor tendon is inserted on the base of the dorsal side of the first phalanx The tendon then becomes broader and divides into 3 portions The middle portion (the central or medial band) is inserted proximal dorsally on the middle phalanx while the other two—extensor lateral bands—continue along this central tendon and finally unite to be inserted on the distal phalanx proximal dorsally The lumbrical tendon from the radial side and the 1st volar interosseus from the ulnar join these 2 lateral portions (Tubiana and Valentin 1964)

According to Duchenne (1867) and Wood Jones (1949) the extensor digitorum communis II can abduct the index finger radially This would mean that this tendon lies radially to the dorso volar axis of the metacarpo phalangeal joint

Flexor digitorum sublimis II

This muscle arises from the ulnar epicondyle of the humerus from the ulna and from the radius A fibrous arcade extends between the ulna and the radius and covers the median nerve at this level Its tendon lies in the carpal tunnel deeper than do the tendons of sublimis III and IV The muscles of the index finger therefore lie deeper and fairly isolated The

sublimis tendon later divides to allow the passage of the tendon of the profundus muscle and is inserted on the volar lateral aspect of the middle phalanx In the finger and in the distal part of the palm the tendon is enclosed in a relatively narrow sheath

Flexor digitorum profundus II

This muscle has a broad origin on the volar aspect of the ulna and the interosseus membrane It seems to be a relatively well isolated muscle It is separated from the common flexor mass It runs through the above mentioned perforation of the sublimis to be inserted on the proximal volar aspect of the distal phalanx In the finger and the distal part of the hand the tendon is enclosed in a fairly narrow sheath

INTRINSIC AND EXTRINSIC MUSCLES OF THE LITTLE FINGER

The little finger is acted upon by 5 intrinsic muscles and 4 extrinsic muscles

INTRINSIC MUSCLES

The hypothenar muscles that act upon the little finger are the abductor flexor brevis and opponens digiti quinti

The abductor digiti quinti is a long thin muscle that takes origin from the pisiform and surrounding ligaments This establishes continuity between the flexor carpi ulnaris and the abductor digiti quinti via the pisiform bone The muscle is inserted on the ulnar aspect of the base of the little finger and spreads up into an aponeurosis in the extensor aponeurosis In this respect the muscle resembles the short abductor of the thumb

The flexor digiti quinti brevis arises more radially in the hand and above all from the hamulus ossis hamati The tendon of the muscle runs in distal direction on the radial side of the tendon of the abductor muscle and is inserted on the ulnar aspect of the basal phalanx of the little finger

The opponens digiti quinti also takes origin from the hamulus ossis hamati and surrounding ligaments and is inserted on the major part of the ulnar facette of the 5th metacarpal Of the three hypothenar muscles this one lies deepest

The little finger is also acted upon by 2 other intrinsic muscles *the 3rd volar interosseus* and *the 4th lumbrical* According to Landsmeer (1955)

this volar interosseus is never inserted osseously on the little finger Both this volar interosseus and the 4th lumbrical extend (fan like) up into the extensor aponeurosis Landsmeer found that the direction of pull of these 2 muscles was always situated on the volar side of the radio ulnar axis in the metacarpophalangeal joint The 3rd volar interosseus must be regarded as an antagonist to the abductor digiti quinti in that it acts and effects radial abduction of the little finger and thereby contributes to adduction in the 4th interspace towards the ring finger

EXTRINSIC MUSCLES

Extensor digiti quinti proprius and extensor communis V

These 2 muscles belong to the superficial extensors The extensor digitorum communis V like the extensor digiti quinti proprius originates from the radial epicondyle of the humerus The tendon of the extensor digitorum communis V runs in the 4th compartment of the ligamentum carpi dorsale while the tendon of the extensor digiti quinti proprius extends in a separate compartment namely the 5th It is known (e g Wood Jones 1949) that the extensor digitorum communis does not always send a tendon to the little finger and then there can be a connection between the extensor tendon (juncturae tendineum) of the ring finger and the extensor digiti quinti proprius

The tendon of the extensor digiti quinti proprius fairly often divides into 2 tendons in the back of the hand The course of the distal segment of the tendon of this muscle and of that of the extensor communis V resembles that of the extensors of the index finger

The extensor digiti quinti proprius runs on the ulnar side of the dorso volar axis in the 5th metacarpo phalangeal joint and can thereby abduct the little finger (Duchenne 1867 Wood Jones 1949)

Flexor digitorum profundus and sublimis V

The 2 flexors of the little finger essentially resembles that of the deep and superficial flexors of the index finger

SUMMARY

A brief review of the normal anatomy of muscles and tendons of the thumb index finger and little finger is presented with special reference to the intrinsic muscles of the thumb

Chapter IV Author's dissection of muscles, tendons, joints and ligaments around the thumb

Opinions in the literature differ concerning the intrinsic musculature of the hand In order to form a personal opinion of the muscle anatomy of the thumb the present writer therefore studied these parts in 13 fresh autopsy (right hand) not embalmed specimens and in one amputated specimen (left hand) Interest was focused mainly on the muscles and tendons presumably taking part in the palmar adduction of the thumb and the various possibilities of insertion of the adductor pollicis on the first ray

The specimens were so fresh that tendons and joints could still be moved The function of the muscles could therefore be partly studied by pulling them in the specimen

ATTACHMENT OF ADDUCTOR MUSCLES ON THE FIRST RAY

Six groups of adductor attachments were found (Table 2)

Insertion No 1 called the adductor aponeurosis (Mondry 1940 Stener 1962) The most dorsal superficial parts of the adductor musculature are attached partly across the extensor aponeurosis (the hood) and partly obliquely in the extensor aponeurosis The last portion of the adductor muscles consists of a delicate tendon extending up into the distal extensor pollicis longus tendon (Fig 5)

Insertion No 2 With strong muscle and likewise strong tendon the deeper part of the adductor musculature is attached to a small tuberosity proximal ulnar and volar on the basal phalanx of the thumb In all of the specimens it was possible to demonstrate the tuberosite interne et superieure de la premiere phalange du pouce (Poirier as quoted by Frohse Fränkel (1908) (Fig 6)

Insertion No 3 No further attachment of the adductor musculature on the dorsal aspect was demonstrable the rest of this musculature being attached to the volar aspect of the thumb Intermediate slips of the adductor mus

Table 2 Attachment of adductor musculature to first ray according to author s dissections

No	Name	Insertion
1 a		Transversally into the hood
1 b	Adductor aponeurosis (*Mondry 1940 Stener 1962*)	*Obliquely into the hood*
1 c		As a tendon out to distal EPL
2	Tuberosite interne etc Loirier as quoted by *Frohse Frankel 1908*	Tuberosity on ulnar volar aspect of basal phalanx
3		Volar capsule of MP joint
4		Ulnar sesamoid bone
5 a		Distal volar radial on first metacarpal bone
5 b	Superficial radial fan	Strands running distally and osseously inserted on volar radial part of basal *phalanx*
5 c		*Strands running distally and* osseously inserted on volar radial part of distal phalanx (prep No 2)
6	Deep radial fan	Along and strengthening fibrocartilago *volaris and more distally*

culature are attached on the volar and ulnar surface of the joint capsule at the level of the first metacarpophalangeal joint

Insertion No 4 A 4th attachment is that which *according to conventional* conception is the most known namely that of the adductor insertion on the ulnar sesamoid bone (Fig 7)

Insertion No 5 The 5th possibility of insertion of the deep part of the adductor musculature proved to consist of superficial (volar) tendons extending fan like (radially) from the adductor musculature past the ulnar sesamoid bone and merging with the volar aspect of the tendon sheath of flexor pollicis longus This superficial fan like arrangement in radial direction divided into three groups in the specimens a) some fibres crossed the tendon to the flexor pollicis longus on its volar side and were attached

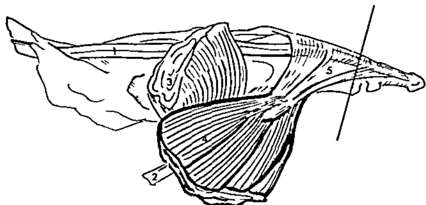




Fig 5 1 EPL 2 FPL 3 Reflected IOD I 4 ADD POLL 5 Adductor aponeurosis

on the volar radial-distal part of metacarpale I b) Relatively strong strands of fibres which were found in all of the dissected specimens and which run in distal radial direction to be attached on the proximal volar radial aspect of the basal phalanx of the thumb (Fig 7) c) In one preparation (No 2) some strands also ran distally and radially and were attached to the radial volar proximal aspect of the distal phalanx osseously

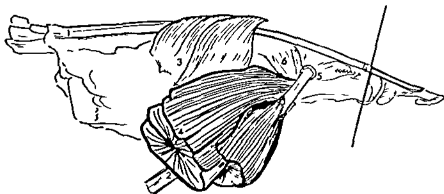


Fig 6 1 EPL 2 FPL 3 Reflected IOD I 4 ADD POLL 5 Tuberosite interne et superieure de la premiere phalange du pouce (Poirier) 6 Ulnar collateral ligament

Insertion No 6 could be demonstrated after the tendon sheath of the flexor pollicis longus had been divided and the tendon was retracted A well defined insertion of the adductor continued with strong strands reinforcing the fibrocartilago volaris (Fig 8) These bundles continued between the ulnar and radial sesamoid bone partly further distally radially finally to be attached osseously on the volar proximal radial aspect of the basal

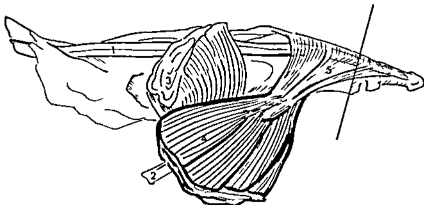




Fig 5 1 EPL 2 FPL 3 Reflected IOD I 4 ADD POLL 5 Adductor aponeurosis

on the volar radial distal part of metacarpale I b) Relatively strong strands of fibres which were found in all of the dissected specimens and which run in distal radial direction to be attached on the proximal volar radial aspect of the basal phalanx of the thumb (Fig 7) c) In one preparation (No 2) some strands also ran distally and radially and were attached to the radial volar proximal aspect of the distal phalanx osseously

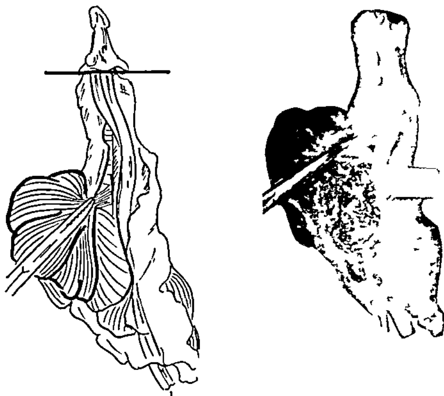


Fig 8 Flexor tendon sheet split up and showing deep insertion of ADD POLL into radial sesamoid bone as a part of fibro-cartilago volaris 1 FPL

metacarpal joint I and somewhat in metacarpophalangeal joint I At the same time the thumb was supinated The extensor pollicis longus was embedded in loose tissue in all of the specimens from a point in the proximal part of the adductor and abductor aponeurosis (the hood) to the level of Lister s tuberosity

The extensor pollicis brevis on the other hand was situated throughout its course in relatively dense or tight tissue and could not be moved sideways to any appreciable extent When the extensor pollicis brevis was pulled in proximal direction it proved to have two functions an extension of the metacarpo-phalangeal joint I and abduction of the carpo-metacarpal joint I which is in agreement with Duchenne s (1867) conception that the extensor pollicis brevis acts as an abductor on metacarpale I The extensor pollicis brevis tendon is attached osseously to a tuberosity on the proximal radial aspect on the basal phalanx In one of the preparations

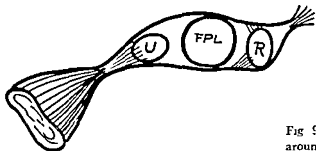
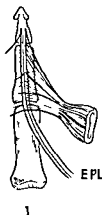
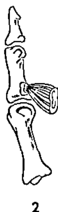
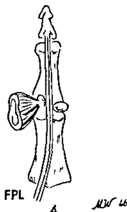


Fig 9 Strands from ADD POLL around FPL











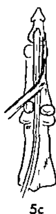




Fig 10 Attachment of ADD POLL 1 Adductor aponeurosis 2 Tuberosite interne etc (Poirier) 4 Ulnar sesamoid bone 5 a Distally on first metacarpal 5 b Proximally on the basal phalanx 5 c On the radial part of the base of the distal phalanx 6 Strong strands reinforcing the fibro-cartilago volaris

(No 11) the extensor pollicis brevis was found to continue distally to become attached also on the proximal-dorsal aspect of the distal phalanx an observation reported previously by Kaplan (1965) When the extensor pollicis brevis was pulled in proximal direction it was followed a few millimetres by the hood The extensor pollicis brevis is however not attached to the abductor aponeurosis but could be traced some millimetres distally below the latter as a free tendon

The abductor pollicis brevis could to a certain extent be regarded as an antagonist of adductor pollicis but also as a synergist As an antagonist it *acts like a pure abductor as a synergist it acts together with the adductor* pollicis by pulling the extensor aponeurosis and the hood in proximal direction as does the extensor pollicis longus (Bunnell 1956) The extensor pollicis longus can here be regarded as a prime mover of tension and proximal pull of the abductor adductor aponeuroses Tendon fibres extending from the adductor and the abductor brevis lie dorsally to the radio-ulnar axis of movement in the metacarpo-phalangeal joint I and thereby extend the distalmost joints of the thumb When the pull of the extensor pollicis longus was released and the deeper part of the adductor pollicis and abductor pollicis brevis were pulled I found like Bunnell (1956) that the abductor adductor aponeurosis slipped in distal direction and that the metacarpo-phalangeal joint I flexed From the musculature of the abductor pollicis brevis 2 tendons could be isolated One of them extended into the hood towards the extensor pollicis longus tendon as a well defined abductor aponeurosis Other strands fairly strong were osseously attached to the volar radial aspect of the basal phalanx of the thumb When this tendon was pulled it flexed and slightly abducted the metacarpo phalangeal joint I

The flexor pollicis longus in its own well defined sheath originating from the middle of the metacarpale I ran in distal direction The tendon of the flexor pollicis longus lay between the bellies of the flexor pollicis brevis and opponens pollicis The tendon could not be displaced sidewards to any appreciable extent

ADDUCTION EXPERIMENTS ON FRESH POST MORTEM SPECIMENS

The specimens were removed from fresh not embalmed autopsy specimens so that the tendons and joints could still be moved Most of the specimens were taken in such a way that part of the distal phalanx, the entire basal phalanx and metacarpale I and multangulum majus as well as parts of the 2nd ray could be dissected Adduction of the metacarpale I towards meta

carpale II could be produced by pulling either the extensor pollicis longus tendon or the adductor musculature Pull of the tendon of the flexor pollicis longus produced no adduction of metacarpale I towards meta carpale II

When the adductor musculature was pulled it tightened the super ficial as well as the deep radiation in radial direction distally see Figs 6—8 Direct continuity was thus found between the adductor musculature and its tendons attached to 1) metacarpale distally 2) basal phalanx proximally and 3) in 1 case (No 2) in the proximal volar aspect of the distal phalanx of the thumb The effect of this pull was therefore adduction pronation and flexion of the carpo metacarpal joint and flexion of metacarpo phalangeal joint and of the inter phalangeal joint in the one case (No 2) where the tendon was inserted far out on the distal phalanx

Certain interesting features of the carpo metacarpal joint I were ob served On adduction of the thumb in palmar direction it was found that the proximal part of metacarpale I slid in radial direction On careful dissection of the ligaments in the carpo metacarpal joint I as previously done by Haines (1944) Gedda (1954) and Napier (1955) found that a strong ligament extending from the proximal dorsal part of metacarpale I converged down to a more isolated point on the distal dorsal radial surface of the multangulum majus This ligament limited the radial gliding move ment of the basis of metacarpale I on adduction The ulnar volar ligament previously demonstrated by Gedda (1954) also limited the movement of this outward sliding of the proximal part of metacarpale I on adduction Radially to the dorsal carpo-metacarpal ligament there is a thin capsule which is not reinforced with ligament. That this capsule is loose and has a yielable radial side may have something to do with its function to allow the outward sliding of the basal part of the proximal metacarpale I (in radial direction) on palmar adduction Adduction thus tightens the strong ligament extending from the distal dorsal radial aspect of the multangu lum majus running fan like in distal direction to its attachment on the dorsal part of metacarpale I The volar ulnar ligament (Gedda 1954) which is thereby also tightened thus works as a limiting ligament in that it prevents hyperextension of the carpo metacarpal joint I The ligament that runs on the dorsal side between the bases of metacarpale I and II (dorsal inter metacarpal ligament) prevents undue abduction of metacarpale I in the first carpo metacarpal joint

After having severed the dorsal carpo-metacarpal ligament adduction in palmar direction was repeated It was found that the basal part of meta carpale I glided out considerably more in radial direction This dorsal carpo metacarpal ligament thus acts as an important guide and brake

EFFECT OF FIRST DORSAL INTEROSSEOUS ON FIRST RAY

On palmar adduction the thumb moves from abduced pronated position to an adduced supinated position towards the volar part of the base of the index finger When the index finger was held still as a fixed part pull of the 1st dorsal interosseous muscle was found to adduct the thumb This is previously known The examination of the specimens showed that the origin of the 1st dorsal interosseous muscle was situated on the dorsal ulnar aspect of the metacarpale I When this dorsal interosseous muscle was pulled it adducted and supinated metacarpale I

SUMMARY

Muscles tendons joints and ligaments were dissected in 14 hand specimens Interest was focused mainly on muscles and tendons presumably taking part in the palmar adduction of the thumb 10 different attachments of adductor pollicis muscle on the first ray could be demonstrated some of them not mentioned before in the literature Some adduction experiments on fresh post mortem specimens were made Adduction movement of the first ray against the second was demonstrated by pulling the extensor pollicis longus tendon which was not the case when the flexor pollicis longus tendon was pulled Some detailed dissections of the CMC joint I gave information on the behaviour of the base of the first metacarpal in this joint during palmar adduction of the thumb Radial sliding of the proximal part of this bone was then always demonstrated and the role of the ligaments around the actual joint was studied

Part III On some normal functions of the hand

Chapter V On some normal functions of the hand

INTRODUCTION

If the hand is regarded as a tool then the arm is the handle The function of the hand is dependent on the precision of its movements combined with strength and stability The performance of these functions requires the highest degree of sensibility of the gripping surfaces so called tactile gnosis (Broman 1945 Moberg 1958) It is this tactile gnosis that makes the hand seeing *i e* even in the dark one can recognize the shape and size of any thing held in the hand

The total function of the hand therefore depends on its movability with strength as well as sensibility and in function tests both must be evaluated preferably quantitatively (Moberg 1958 1964)

SHORT SURVEY OF SOME FUNCTIONS OF THE 3 MAIN NERVES OF THE HAND

The radial nerve governs muscles and movements taking part in stabilisation of the wrist and opening of the grip The nerve has a special area of innervation *i e* in the first interspace and therefore partakes in the key grip

The median nerve supplies impulses from the most important tactile surfaces of the hand The nerve gives off motor branches to the abductor pollicis brevis opponens pollicis and the superficial head of flexor pollicis brevis besides the two radialmost lumbricals The nerve therefore governs abduction and opposition movements of the thumb and broadly speaking it may be regarded as one of the most important nerves of the hand

The ulnar nerve occupies from a functional point of view an intermediate position between the radial nerve and the median nerve because it covers a fairly important tactile surface in the ulnar part of the hand and because it governs muscles and movements of all of the small muscles of the hand except those innervated by the median nerve Thus the ulnar nerve is said to be responsible for the fine adjustment of many of the small movements of the hand while the median nerve receives impulses from the most important tactile surfaces in the hand

In ulnar paralysis the sensibility of the gripping surfaces on the radial aspect of the fingers is thus unimpaired Certain function tests of such a hand are therefore not disturbed by loss of sensibility occurring in complete injury to the median nerve

METHODS FOR QUANTITATIVE EVALUATION OF THE SENSIBILITY OF THE HAND

Brief review

The great importance of sensibility for adequate function of the hand is now so well known and has been examined so thoroughly by Hilgenfeldt (1950) Bunnell (1956) Moberg (1958 1962 1964) and Önne (1962) that it does not require further discussion here

The examination methods now used are two point discrimination (Weber 1835 Moberg 1958 Önne 1962) the ninhydrin method (Moberg 1958 Önne 1962) the picking up test (Moberg 1958) and demonstration of signs of wear and tear (Moberg 1958 Mannerfelt 1962) These methods allow good evaluation of the sensibility of the hand

CONSIDERATIONS ON QUANTITATIVE MEASUREMENTS OF THE STRENGTH OF HAND MUSCLES

Methods for measuring the strength of the hand have long been available The literature in this field is fairly voluminous Good surveys have been given by Hunsicker and Donelly (1955) and Tornvall (1963) The following methods have been used for measuring isometric contraction

1 Mechanical spring balance methods
2 Cable tension methods
3 Hydraulic methods
4 Pneumatic systems
5 Strain gauge methods

The examination methods fall largely into 2 groups One working with ergometers (measurers of work performed) and ergographers the other comprising simpler methods using dynamometers (measurements of strength) and suitable for clinical use

SURVEY OF ERGOMETERS ERGOGRAPHS AND MORE COMPLICATED INSTRUMENTS FOR MEASURING THE STRENGTH OF THE HAND

According to Martin (1921) an ergograph is an apparatus for recording successive muscle contractions It records the beginning of a contraction its duration and its cessation These measurements can be recorded mechani

cally or electronically Common to these apparatuses is that the strength of various muscle functions can be measured while the patient is performing certain grips or movements of the hand (Brahme 1936 Hellebrandt Kelso and Eubank 1950 Beasley 1956 Asmussen Heeboll Nielsen and Molbech 1959 Beasley 1961 Ebskov and Bonde Petersen 1963) These apparatuses allow some detailed examinations of the hand but they are complicated They are also expensive and less suitable for routine clinical work they are often large and not easy to use These apparatuses were designed mainly because no simple reliable methods were available for measuring the strength of the hand and certain muscles of the hand

SURVEY OF DYNAMOMETERS SUITABLE FOR CLINICAL USE

Martin (1921) defined a dynamometer as an apparatus useful for numerical estimation of the strength of a single contraction of a muscle One of the oldest and most well known dynamometers in daily use is Regnier s dynamometer (1807) which forms the basis of most spring steel dynamometers in use to day It was Collin who developed such dynamometers at the end of the 19th century (Collin s dynamometer — as quoted by Zoth 1936) Whipple (1914) described a pull dynamometer with a handle The pull applied was recorded on a dial Lovett and Martin (1916) developed another method according to which the eccentric strength of various muscles was measured They used a break method They measured the breaking strength of muscles *i e* the muscular force required to overcome maximal resistance The authors used their apparatus for measuring the strength of ulnar adduction of the adductor pollicis for example They did not give any values obtained by systematic examination with this method Lewey Kuhn and Juditski (1947) published a method according to which with the aid of a grip connected to a spring balance they recorded the strength of certain hand functions under more standardised conditions The mechanics of the apparatus is based on stretching of steel springs Differences of less than half of pound were regarded as lying within the error of the method when testing the strength of the small muscles of the hand Newman (1949) constructed a myometer with an inbuilt *hydraulic system The instrument has an extra indicator (a maximum* reader indicator) Wainerdi (1950) constructed a grip dynamometer based on the principles according to which the strength is measured by compression of an air balloon The force applied was registered on a dial Bechtol (1954) devised a grip dynamometer which was excellent in several respects It had the advantage that it could be adjusted to fit hands of different sizes The instrument is known as the Bechtol Jamar dynamometer

A wide variety of dynamometers has been designed mainly because Collins original dynamometer was both unreliable and complicated The following objections have been raised against Collins dynamometer (Whipple 1914 Brahme 1936)

1 The time between two successive examinations is relatively long because reading of the result and a second grip of the instrument take time

2 Collins dynamometer does not allow examination of the duration of maximum exertion nor how the grip is loosened slowly or rapidly

3 Collins dynamometer can only be used by a painless hand When used for estimating the strength of painful hands the values recorded will be misleadingly low

4 In sweaty hands the dynamometer is apt to slip

5 Collins dynamometer is not constructed in such a way as to fit automatically into correct position in the hand If the dynamometer is not gripped in the proper way the values will be artificially low

SUMMARY

After a brief review of methods now used for evaluation of the sensibility of the hand a short survey is given of useful methods for measuring the strength of isometric contractions in the hand Several apparatuses of dynamometer type are based on Regnier s (1807) principle with a spring steel dynamometer

Chapter VI Quantitative methods for evaluating strength of muscles supplied by ulnar nerve

PREVIOUS METHODS

The literature on the symptoms and signs of paralysis of the ulnar nerve is abundant. But only few investigators have tried to estimate the loss of function quantitatively with special dynamometers. Some investigators used Collin's dynamometer and found half to two thirds of the strength of the hand to be lost in ulnar paralysis (Bunnell 1956 and others). Lowett and Martin (1916) measured the strength of ulnar adduction of the thumb. Pollock (1925) like Lowett and Martin (1916) used a spring scale dynamometer for measuring muscle strength. The apparatus was inserted between the hand of the examiner and that part of the patient to be examined. The authors gave no control values. Lewey, Kuhn and Juditski (1947) measured the strength of some grips dependent upon the ulnar nerve. They also used a spring scale dynamometer inserted between the examiner and the patient's hand. The normal value for abduction of the index finger was 9.0 lbs (=4 050 g), abduction of the little finger 8.9 lbs (=4 005 g) and ulnar adduction of the thumb 10.4 lbs (=4 680 g). The strength of abduction of the index finger and little finger was measured during isometric contraction. On adduction of the thumb the examinee gripped a disk between the index finger and the thumb with all joints extended. This disk was connected to a spring scale which was pulled with increasing force towards and by the examiner. The error of the method according to the authors was less than 1/2 pound (250 g). The authors gave no values for patients with ulnar paralysis.

Moberg (1948) measured the pinching grip with a spring scale to which was connected a metal disk. The examiner pulled the spring scale while the patient tried to hold the metal disk between his index finger and thumb. When the disk slipped out of the patient's grip the value was noted by a maximum reading indicator on the scale. Normal values for the pinching grip are not given.

Newman (1949) designed a myometer based on the hydraulic principle for measuring isometric contractions. The author recorded the strength of abduction of the index finger and the little finger of the abductor pollicis brevis but not the strength of palmar adduction of the

thumb The strength of adduction in the 2nd and 4th interstices could not be measured with this apparatus either The normal range of values was not given

Zadig (1962) designed a dynamometer based on the hydraulic principle It is true that the apparatus was designed for measuring the strength of the arms and legs but the pinching grip could also be measured with it The examinee is instructed to compress the apparatus otherwise used for measurement of the strength of the pull According to Zadig (1962) various objections can be raised against the use of apparatuses in which the strength is measured by compression of an apparatus

1 It is difficult to hold the apparatus still

2 Apparatus for measuring resistance requires special plates for appplication of pressure

3 Application of such a plate can be painful to the patient

4 It is difficult to control the direction of the counterpressure The force should always be directed at right angles to the lever

In view of these disadvantages Zadig tests muscle strength by resistance to pull

In an elctromyographic investigation of certain movements of the fingers governed by the ulnar nerve Egawa (1959) used a small balloon which when compressed actuates a mercury column With this apparatus he studied the pinching grip betwen the thumb and the ringfinger of 2 controls and of 2 patients with ulnar paralysis The normal value for this special pinching grip was 80 mm Hg

After the ulnar nerve had been blocked in the controls the value was 40 mm Hg Electromyographically Flexor digitorum sublimis IV worked much more than profundus IV in pinching grip between the thumb and ring finger after ulnar nerve block

Discussion

Most of the dynamometers described above can be used for measuring some movements of the hand governed by the ulnar nerve Hardly any dynamometer can measure the strength of all these tests

1 the pinching grip
2 palmar adduction of the thumb
3 radial abduction of the index finger
4 adduction in the 2nd and 4th interspaces and
5 ulnar abduction of the little finger

These 6 tests are useful mainly in the examination of ulnar function Only one publication (Lewey Kuhn and Juditski 1947) gave the normal values for some of these movements based on systematic examination of a large series Some apparatuses register the strength of the pinching grip when the examiner between a dynamometer and the patient s pinching grip intro duces a spring scale and a small metal block Sweating of the hand is a source of error in this method

It would appear that no systematic investigation using a suitable meas uring instrument have been made of the residual function of the hand in a large series of ulnar paralysis Isolated measurements of the strength of single groups of muscles have been reported but no analysis has been made of the strength of those groups of hand muscles controlled by the ulnar nerve It therefore seemed necessary to construct an apparatus with which it would be possible to measure as many as possible of the grips and movements of the hand that are controlled partly or entirely by the ulnar nerve

An apparatus satisfying these requirements was therefore designed by the author and is described in the next part of this chapter

DESCRIPTION OF THE AUTHORS DYNAMOMETER

Purpose of the construction

The purpose was to design an apparatus fitting the following require ments

a The method should be standardisable
b The measurements should be precise and reproducible
c The method should preferably be useful for both clinical and research use
d The dynamometer should be able to measure isometric muscle contrac tions

a—c are the requirements also set up by Beasley (1961)

The term isometric muscle contraction is now generally accepted On such a contraction the origin of the muscle and its insertion do not approach one another or if so only very slightly It is a product of energy or strength and the work performed can be expressed biologically as strength ×time (Hettinger 1964)

Range of use

The special dynamometer was originally designed to measure the strength of the palmar adduction of the thumb I have however found that also

to construct an apparatus with which it would be possible to measure the strength of the grips and movements of the hand that are controlled partly or entirely by the ulnar nerve A dynamometer satisfying these requirements was therefore designed by the author The construction mode of action range of use and the method to calibrate the dynamometer are described

The effect of temperature and relative humidity on the dynamometer was investigated An examination in a climate chamber showed that variation of temperature between 15 0° C and 25 0 C at a relative humidity of 75 % had no effect on the accuracy of the dynamometer This investigation was based on the lowest and highest temperatures in the author s laboratory while measuring the strength of grips and movements in the hand both in controls and in volunteers subjected to ulnar nerve block

During all these measurements the two steel plates of the dynamometer were compressed more than 30 000 times It was therefore necessary to re calibrate the dynamometer now and then during the investigation The control calibrations gave practically identical curves which made it possible to compare values from the beginning of the investigation to the end (Oct 1962 to May 1964)

Chapter VII Control series

COMPOSITION

The control series consisted of 100 persons (50 male medical students and 50 female students of physiotherapy) aged 18 to 29 years 88 per cent of the males were between 19 and 24 years and 78 per cent of the females were between 20 and 23 years In Asmussen and Heeboll Nielsen s (1961) large series of males and females aged 15—60 years the highest value for isometric contractions were noted for subjects between 18 and 30 years

None of the 100 controls had had any disease known to affect the central or peripheral nervous system nor had any of them any serious injuries to the hands in their history Four males and 1 female were left handed

ORDER OF TESTS PERFORMED

1 Strength of pinching grip
2 Strength of palmar adduction of the thumb
3 Strength of radial abduction of the index finger
4 Strength of adduction in the second interspace
5 Strength of adduction in the fourth interspace
6 Strength of ulnar abduction of the little finger

METHODS AND STANDARD POSITIONS

Measurements were always made of the better hand

The temperature and the relative humidity in the examination room were measured

The examinee was never allowed to see or hear the values recorded The values were therefore never read aloud but recorded directly by an addition machine on a strip of paper after every test (Fig 14) The subjects were therefore not induced to compete with other controls or to achieve higher values than at a previous test

The subject was instructed not to be tense but to concentrate entirely on the actual test

Jerky tests and tests in which the subjects evidently overexerted themselves or in which they pushed the lower arm forwards were not accepted



Fig 13 Palmar adduction of th thumb

The control group was examined and measurements were made as planned on day 1 and on day 13

The experimental subjects were studied on day 1 on day 7 before and immediately after the induction of ulnar block and again on day 13 A small group of male students were examined daily for 13 days

In order to keep the conditions under which the measurements were made as standardised as possible the hand to be studied was adjusted and fixed in exactly the same way in relation to the active part of the dynamometer *i e* the pressure plate from one occasion to another For this purpose a special fixation arrangement—an examination bridge—was designed It consisted of a stationary and a movable part (Figs 13—18)

The upper arm the elbow and the lower arm was fitted in and fixed to the stationary part The elbow was set at 90° flexion At this angle the strength in pro supination is greatest (Salter and Darcus 1952) The lower

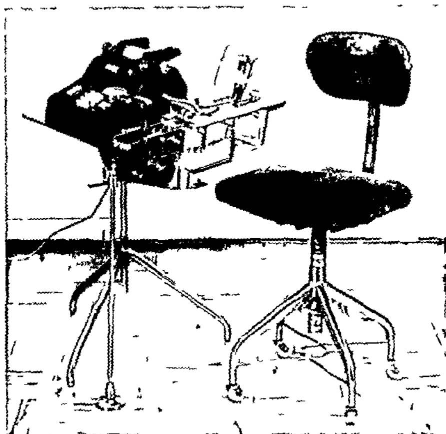


Fig 14 General view of equipment.

arm was therefore held in midposition between pronation and supination by a transverse strap fixed around the distal part of the lower arm (Fig 18). The lower arm was resting in a gutter.

According to the plan of the examination the strength of the pinching grip, the strength of palmar adduction of the thumb and radial abduction of the index finger were to be measured at varying angles of the wrist. In the examination bridge the wrist could be moved around its radio-ulnar axis (volar flexion — dorsal extension). This axis runs through the centre of an egg (Hjortsjö 1959). The axis of movement extending from pole to pole of the egg runs approximately through the centre of the caput ossis capitati (Forsell 1902, Wright 1959, Hjortsjö 1959). The outer and ulnar projection of this level onto the wrist lies approximately at the level of the os pisiforme palpable from the outside (Fig 18). After the upper arm, the lower arm and the hand had been placed in the bridge rotation

Fig 15 Radial abduction of the index finger The strength is measured against breaking force Observe the two contact plates between index and long finger

Fig 16 Close up of parts of attachment for the dynamometer and measuring device

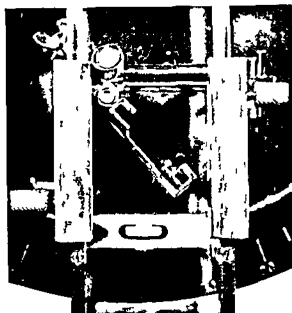


Fig 17 Close up of attachment for the dynamometer

Fig 18 Pinching grip Observe the special bridge for adjusting the thumb in pronation The pisiforme bone is adjusted to the axis of movement of the device.

about the radio ulnar axis of the wrist was possible and this was done around a largely vertical axis in the movable part of the fixation range (Fig 16) The movable part of the fixation devise can move about 75° dorsally and 75° volarly around its axis

In this movable part of the bridge the dynamometer is mounted on a fixed part adjustable in two directions at right angles to one another and can be locked in desired position The stationary arrangement for the dynamometer is thus movable in proximal distal direction and laterally (Fig 16) Movement to one side or the other corresponds to dorsal volar in relation to the lower arm in midposition between pronation and supination The dynamometer can also be turned about a vertical axis in the distal fixation arrangement (Fig 17) The rotation is necessary for adjustment of the best position of the dynamometer when measuring the pinching grip All adjustments can be set and registered on a millimeter scale (Figs 16 and 17) Possibilities of variation are necessary because of differences in arm length and hand size of the person examined The best standard position in the coordinate system for a given patient is recorded exactly The same subject can therefore be examined in exactly the same position from one occasion to another

Special reference lines were drawn the first time the hand was placed in the examination bridge namely for

palmar adduction of the thumb at the level of the IP joint ulnarly (see Fig 13)
radial abduction of the index finger on the radial side at the level of the PIP joint of the index finger (Fig 15)
adduction in the 2nd interspace on the radial side at the level of the PIP joint of the long finger
adduction in the 4th interspace on the ulnar side at the level of the PIP joint of the ringfinger
ulnar abduction of the little finger on the ulnar side at the level of the PIP joint of the little finger

The movable sledge (Figs 16, 17) is used for fastening the dynamometer when measuring the strength of *the pinching grip* and *palmar adduction* In the latter case a T formed support locks the 4 ulnar fingers (Fig 13) A special bridge replaces this sledge when measuring the strength of *radial abduction of the index finger* (Fig 15) This special arrangement keeps the hand fixed and the only movable part is the index finger, which performs radial abduction against breaking force To secure stability in lateral direction the index finger is guided by a side support Contact plates are applied to the ulnar side of the index finger and the radial side of the long finger The subject is instructed to perform maximal radial abduction

with the index finger The examiner presses the dynamometer in ulnar direction and with the plate of the dynamometer in proper position against the reference line drawn at the level of the PIP joint radially on the index finger (Fig 15) The subject is gradually unable to resist the increasing pressure and the two metal plates come into contact with one another and thereby close an electric circuit which starts an electric buzzer The value on the dial is then read During this examination the thumb is abducted

In the measurement of the strength of *ulnar abduction of the little finger* the gutter holding the lower arm is raised This examination is carried out under somewhat less standardised conditions the hand being stabilised only by the subject s other hand The same fixation technique is used as for measurement of the strength of *adduction in the 2nd and 4th inter spaces*

In 3 of these last mentioned tests contact plates are applied to the two surfaces which later contact one another

The examination apparatus is constructed in such a way that its use for the contralateral hand requires only a few simple manipulations

SPECIAL TESTS

Strength of pinching grip

In this and the following 5 tests the subject sat comfortably beside the examination bridge in which the upper and lower arm was strapped with the elbow flexed 90 and the lower arm in midposition between pro nation and supination The pisiform bone was placed exactly over the vertical axis of rotation of the examination bridge (Fig 18) With the aid of an extra small bridge the thumb was placed in a suitable pronated position against the pressure plate (Fig 18) The examinee was instructed to perform a firm round pinch which was demonstrated The strength of the pinching grip was measured in 3 successive tests at 5 different angles of the wrist (—30 ±0 +30 +50 +70° see definitions) At +30 the metacarpale I was in line with the lower arm Only the thumb and the index finger were examined in this test the 3 other ulnar fingers were extended actively by the patient Short pauses between the tests were allowed

Strength of palmar adduction of the thumb

The patient was sitting with the upper and the lower arm and wrist in the examination bridge

A reference line was drawn at the level of the IP joint on the ulnar aspect of the thumb This reference line coincides with the midline of the pressure plate on the dynamometer (Fig 13) The thumb presses the plate

in ulnar direction Three tests at 5 different angles of the wrist joint were performed (—50 —30° ±0 +30 +50° see definitions) On change of angle of the wrist the instrument had to be reset so that the reference line of the thumb coincided with the midline of the black plate of the dynamometer The 4 ulnar fingers were kept extended in all joints and were guided by a special T shaped support (Fig 13)

Strength of radial abduction of the index finger

The patient was sitting with the upper and lower arm strapped in the examination bridge The entire hand with exception of the index finger was placed in a special holding device A reference line was drawn radially at the level of the PIP joint of the index finger The breaking force was measured Three tests were performed at 3 different angles of the wrist joints (—30° ±0° +30 see definitions) Measurement of radial abduction of the index finger measures of course not only the interosseus dorsalis I but probably also extensor digitorum communis II and the first lumbrical

Strength of adduction in second interspace

The patient was sitting with upper and lower arm in the examination bridge A reference line was drawn at the level of the PIP joint on the radial side of the long finger The hand to be examined was supported by the examinee s other hand Three test with extended (180°) and flexed (120°) MP joints were done with the wrist joint at an angle of ±0° (see definitions)

Strength of adduction in fourth interspace

The examination was identical with the last mentioned one except that the adduction strength between the little finger and the ring finger was tested A reference line was drawn on the ulnar side of the ring finger at the level of the PIP joint

Strength of ulnar abduction of the little finger

The gutter supporting the lower arm was raised 10 cm The examinee supported the hand to be examined with the other hand The strength of ulnar abduction of the little finger was measured against breaking force in essentially the same way as in the examination of the index finger But here 3 tests were done at only 1 angle (±0°) of the wrist but with the MP joint V at 180° and at 120

Ulnar abduction of the little finger must be regarded as the result of a combined action of abductor digiti quinti extensor digitorum communis V and extensor digiti quinti proprius

RESULTS

Error of the method

The error of the method — ε — is given in degrees of the dial of the dynamometer and was calculated according to the following formula

$$\varepsilon = \sqrt{\frac{\Sigma\Sigma(X_{ij} - M_i)^2}{N(n-1)}} \quad \text{where}$$

i = one of the fifty controls between numbers 1 and 50
j = one of the three measurements
X_{ij} = the value measured for the ith person in the jth measurement.
M_i = arithmetic mean of the three measurements in a given test for the ith person.
N = number of subjects studied
n = number of measurements in the test

The error of the method reflects the accuracy of the method and is based on measurements made in the controls (50 males 50 females)

The above formula is generally applicable and can therefore be used in the estimation of the error of the measurements in the group in which the ulnar nerve was blocked

The error of a single measurement in a person with the wrist extended (angle = +30°) and for the pinching grip was ±1.3 on the scale of the dynamometer with 68 % certainty If one chooses instead the accuracy for 95 % or 99.7 % ε must be doubled or trebled Is this error small? The error of the method in per cent of the actual mean value in a given test is presented in Table 5 For the pinching grip for example with the wrist in ±0° ε is 6 % for the males The error of the method is generally between 5 and 7 %

In the discussion of the error of the method two points must be considered namely (1) difficulty in reading the value from the dial and (2) the variation in the ability of the examinee in the final phase of the isometric contraction to maintain a constant pressure so that the indicator on the dial does not quiver too much

Together with an assistant almost 11 000 measurements were made of the controls Occasionally the assistant recorded the value indicated while I studied the actual grip Sometimes both of us read the values simultaneously and the differences between our recordings were insignificant

Judging from the analysis above the accuracy of the method was satisfactory

Standard deviation

Only the better hand was examined with the dynamometer The means were calculated for the controls as the arithmetic mean of the median values of the 3 measurements for each person The standard deviation was calculated with the formula

$$s = \sqrt{\frac{\Sigma(X_i - M)^2}{N-1}} \quad \text{where}$$

X_i = the median value measured for the ith person
M = arithmetic mean of the median values of the 3 measurements on every person
N = number of persons

Table 5 Error of method — ε — in controls

Examination	Angle of wrist	Angle of MP joint	ε	$100\frac{\varepsilon}{M}$	Normal values N	M	s
Pinching grip							
♂	+30	—	13	6	50	233	57
♀			11	6	50	171	36
Palmar adduction of thumb							
♂	±0	—	6	5	50	141	31
♀			7	6	50	109	26
Radial abduction of index finger							
♂	±0	180	10	4	50	245	40
♀			10	6	50	186	38
Adduction in second interspace							
♂	±0°	180	7	7	50	94	19
♀			7	9	50	91	13
Adduction in fourth interspace							
♂	±0	180	5	7	50	66	22
♀			7	11	50	52	22
Ulnar abduction of little finger							
♂	±0	180	6	6	50	101	19
♀			6	7	50	83	9

Results of studies on controls

The mean values noted for the controls on days 1 and 13 are given in Tables 6—12 at the end of this Chapter These tables give the values noted at different angles of the wrist and include also the number of subjects studied and the arithmetic mean of the median values of the 3 measurements on each person The standard deviation was calculated according to the above formula.

Comments

Pinching grip

1 The values noted for the male students were invariably larger at all angles of the wrist than those noted for the females

2 No appreciable difference was noted between the values noted on the 13th day and those noted on the 1st day

3 In both sexes the lowest values were noted when the wrist was dorsally extended maximally (+70°) At other angles of the wrist the values were higher and equally high

Palmar adduction of the thumb

1 The values noted at all angles of the wrist were higher for the males than for the females

2 The lowest values were noted for the 2 extreme positions of the wrist *i e* dorsal extension and volar flexion

With the wrist dorsally extended the extensor pollicis longus cannot act to the same extent as an adductor substitute (Fick 1845 Duchenne 1867) Maximal volar *flexion of the wrist (—50°) also reduces the strength of* palmar adduction The extensor pollicis longus tendon then lies over the first metacarpal and in this position it is probably close to the axis of movement on the palmar adduction This point is discussed further in Chapter VIII

Radial abduction of the index finger

In both sexes the lowest values were noted when the wrist was in volar flexion

Why is the strength of radial abduction of the index finger reduced when the wrist is flexed volarly? The origin and the insertion of the interosseus dorsalis I is the same in both positions In volar flexion of the wrist the effect of long flexors is decreased because the origin and the insertion are then closer to one another (active insufficiency Hjortsjo 1959) It is therefore possible that also the first lumbrical becomes slack One might also imagine that the extensor digitorum communis II of the index finger is of almost maximum length and in this position becomes weaker It is known that the amplitude of the extensor tendons is smaller than that of the flexor tendons (Strandell 1955 Bunnell 1956)

Change in strength of adduction in the 2nd and 4th interspaces as well as of ulnar abduction of the little finger with the metacarpo phalangeal joints flexed

The values increased with increasing flexion of the metacarpo phalangeal joints in the measurement of adduction in the 2nd and 4th interspaces while ulnar abduction of the little finger became weaker with increasing flexion of the metacarpo-phalangeal joint

Table 5 Error of method — ε — in controls

Examination	Angle of wrist	Angle of MP joint	ε	$100\frac{\varepsilon}{M}$	Normal values N	M	s
Pinching grip							
♂	+30	—	13	6	50	233	5[illegible]
♀			11	6	50	171	36
Palmar adduction of thumb							
♂	±0	—	6	5	50	141	31
♀			7	6	50	109	26
Radial abduction of index finger							
♂	±0	180	10	4	50	245	40
♀			10	6	50	186	38
Adduction in second interspace							
♂	±0	180	7	7	50	94	19
♀			7	9	50	91	13
Adduction in fourth interspace							
♂	±0	180	5	7	50	66	22
♀			7	11	50	52	22
Ulnar abduction of little finger							
♂	±0	180	6	6	50	101	19
♀			6	7	50	83	9

Results of studies on controls

The mean values noted for the controls on days 1 and 13 are given in Tables 6—12 at the end of this Chapter These tables give the values noted at different angles of the wrist and include also the number of subjects studied and the arithmetic mean of the median values of the 3 measurements on each person The standard deviation was calculated according to the above formula

Comments

Pinching grip

1 The values noted for the male students were invariably larger at all angles of the wrist than those noted for the females

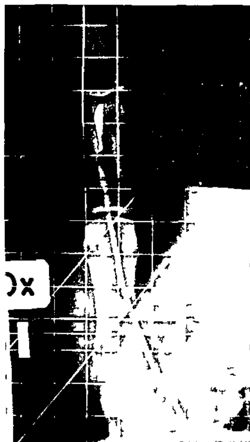


Fig 20 Thumb in resting position between abduction and adduction The EPL tendon is marked with barium contrast.



Fig 21 Palmar adduction of the thumb with hard pressure on the plate of the dynamometer Observe the position of the base of the first metacarpal in the CMC joint I

19) how the tension in the abductor pollicis longus tendon suddenly decreases I have ascribed this to what happens in the CMC joint I in the final phase of palmar adduction (Cf Chapter IV) where the base of the first metacarpal slides out in radial direction in this joint see Figs 20 21 The roentgenograms were taken with the hand in the examination bridge in standard position The extensor pollicis longus tendon is marked with barium contrast The first picture (Fig 20) shows the thumb in resting position between abduction and adduction the second reproduction (Fig 21) shows how the thumb on marked adduction changes its position in the CMC joint I The base of the first metacarpal slides out in radial direction

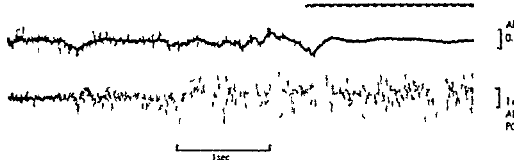


Fig 19 Palmar adduction of thumb against resistance In APL muscle a bipolar needle electrode in ADD POLL muscle a concentric needle electrode The marking indicates the moment when the thumb with force presses against the volar proximal part of the index finger

direction it is stabilised by several muscles namely the adductor pollicis abductor pollicis brevis flexor pollicis brevis flexor pollicis longus and in certain positions also by the weight of the thumb In the radial direction it is stabilised by the extensor pollicis brevis (Duchenne 1867) and the abductor pollicis brevis and longus

In ulnar direction the thumb is stabilised mainly by the adductor pollicis and interosseus dorsalis I The extensor pollicis longus or flexor pollicis longus also stabilise the thumb in ulnar direction (Table 27) page 143

If any of these structures are insufficient palmar adduction cannot be performed under standardised conditions Thus the thumb drops in radial paralysis or in rupture of the extensor pollicis longus in such a way that the thumb can no longer reach and contact the volar proximal surface of the index finger The performance of a coordinated and balanced palmar adduction movement thus requires the action of several muscles innervated by the radial nerve the median nerve and the ulnar nerve

PERSONAL INVESTIGATION OF NORMAL PALMAR ADDUCTION OF THE THUMB

The examination was carried out under standardised conditions with the hand in the examination bridge

If the thumb starts palmar adduction movement from maximal abduction the tendon of the abductor pollicis longus can be felt to be tight at the level somewhat proximal to the first metacarpal During palmar adduction movement this tendon is still tight but in the final phase when the ulnar lateral surface of the thumb presses hard against the volar proximal part of the index finger it can be felt and seen by aid of electromyography (Fig

Table 6 Mean values in kg on day 1 for 50 male and 50 female volunteers

	PINCH	ADD POLL	ABD II	ADD II i	ADD IV i	ABD V
Position of wrist joint	+30	±0	±0	±0	±0	±0
Position of MP joint	—	—	180	180	180	180
♂	4 75	2 85	4 9	2 35	1 45	2 55
♀	3 8	2 45	3 9	1 7	1 4	2 0

Table 7 Mean values pinching grip in control series

Position of wrist joint		+70			+50			+30			±0			—30		
Sex	Day	N	M	s	N	M	s	N	M	s	N	M	s	N	M	s
♂	1	50	160	32	50	209	36	50	214	36	50	218	36	50	214	35
	13	50	158	41	50	210	39	50	221	44	50	222	43	50	208	44
♀	1	6	122	52	50	163	39	50	169	37	50	168	38	6	161	33
	13	6	118	34	50	166	33	50	175	35	50	172	38	6	174	31

Table 8 Mean values palmar adduction of thumb in control series

Position of wrist joint		+50			+30			±0			—30			—50		
Sex	Day	N	M	s	N	M	s	N	M	s	N	M	s	N	M	s
♂	1	50	108	27	50	122	28	50	127	27	50	125	25	50	115	22
	13	50	114	25	50	127	26	50	133	27	50	131	27	50	120	27
♀	1	6	102	10	50	107	19	50	111	18	50	113	20	6	111	19
	13	6	103	17	50	109	20	50	113	20	50	117	21	6	116	11

Table 9 Mean values radial abduction of index finger
in control series

Position of wrist joint		+30			±0			—30		
Sex	Day	N	M	s	N	M	s	N	M	s
♂	1	50	212	36	50	220	34	50	197	34
	13	50	220	37	50	223	34	50	207	29
♀	1	50	171	30	50	177	29	50	163	29
	13	50	174	28	50	180	27	50	166	27

A certain laxity admits in radial direction occurs in the MP joint of the thumb also and here as much as the ulnar collateral ligament allows. The dorso-volar axis of movement of the palmar adduction thus cannot lie in the CMC-joint but distally to it. The position of the axis of movement of the first metacarpal is discussed in further detail in the analysis of the possibilities of palmar adduction of the thumb in ulnar paralysis (See Chapter X).

The known pronation and supination movements of the long axis of the thumb in abduction adduction (Duchenne 1867) were also observed in the present investigation of the palmar adduction movement. It would therefore appear justified to speak of an abduction pronation movement and an adduction supination movement.

SUMMARY

The strength of a number of grips and movements at different angles of the wrist and the MP joints were measured under standardised conditions with the author's dynamometer in 100 controls. These values were used as reference in the estimation of the residual capacity of the hand in ulnar paralysis (Chapter X).

Changes of positions in the radioulnar axis of the wrist had no influence on the values for pinching grip except in position +70 (see definitions). Within positions +30 and —30° the values in palmar adduction of the thumb also were equal. With the wrist flexed to position —30° the strength of the radial abduction of the index finger was lowest. The probable reason for this is discussed. Strength of adduction in the second and in the fourth interspace increased with the MP joints in flexion. Strength of ulnar abduction of the little finger decreased with the MP joint in flexion. The reasons for this discrepancy is discussed.

Statistical treatment of the values obtained is given in tabular form at the end of this Chapter.

An analysis of the palmar adduction of the thumb under normal conditions was performed. With the aid of roentgen and electromyographic examinations the author has showed that the axis of movement of the palmar adduction cannot lie *in* the CMC-joint I but somewhat distal to it. This is discussed in detail in Chapter X.

Part IV Clinical picture in ulnar nerve paralysis

Table 10 Mean values adduction in second interspace in control series

Position of MP joint		180			120		
Sex	Day	N	M	s	N	M	s
♂	1	50	105	20	50	134	24
	13	50	109	17	50	134	23
♀	1	50	76	14	50	109	24
	13	50	80	15	50	113	24

Table 11 Mean values adduction in fourth interspace in control series

Position of MP joint		180°			120		
Sex	Day	N	M	s	N	M	s
♂	1	50	66	15	50	102	19
	13	50	68	17	50	105	19
♀	1	50	64	18	50	86	18
	13	50	61	13	50	89	16

Table 12 Mean values ulnar abduction of little finger in control series

Position of MP joint		180			120		
Sex	Day	N	M	s	N	M	s
♂	1	50	116	18	50	87	18
	13	50	1[illegible]3	22	50	88	16
♀	1	50	89	15	50	64	18
	13	50	90	12	50	57	18

Chapter VIII Clinical picture in ulnar nerve paralysis

In ulnar paralysis the muscle balance in the hand will be so upset from loss of action of the intrinsic muscles that the hand will have lost its skill and be awkward at work (Boyes 1964)

HISTORICAL

The clinical picture of ulnar paralysis has long been known As early as 1832 Calder gave a brief description of some of the features of the clinical picture of injury to the ulnar nerve at the level of the sulcus

Duchenne (1867) may be regarded as the first to have analysed the imbalance of the muscles and its cause in ulnar paralysis Duchenne demonstrated the functions of the muscles of the hand by faradization With this method he showed *inter alia*

1 that in paralysis of interosseus dorsalis I the index finger could be abducted in radial direction by the extensor digitorum communis II
2. that on stimulation of the extensor indicis proprius the index finger was abducted in ulnar direction
3 that the little finger was abducted in ulnar direction on stimulation of the long extensors of the hand (Duchenne thought, however that even Galenus had shown how the action of the extensor musculature of the 4 ulnar fingers produced spreading of the fingers)
4 that the little finger could not be adducted radially towards the ring finger on stimulation of the long flexors of the hand
5 that the thumb was adducted towards the index finger on stimulation of the extensor pollicis longus (This had already been shown in 1845 by Fick who called the extensor pollicis longus extensor pollicis adducens")
6 that on stimulation of the flexor pollicis longus the thumb was not adducted towards the index finger

In model experiments and in cadavers Duchenne investigated the cause of clawing *i e* hyperextension in metacarpo-phalangeal joints and flexion of the proximal and distal interphalangeal joints in isolated intrinsic paralysis. He appears to have been the first to demonstrate how the interossei and lumbrical function as extensors of the 2 distal phalanges and as flexors of the proximal phalanx

Certain objections can be raised against Duchenne s technique For ex

ample he studied the effect of individual muscles with the aid of faradization but without having influenced the antagonists Neither did he analyse the action of the muscles taking part in grip functions He also admitted that faradization was only of limited value in investigation of function of the thumb Nevertheless his work of 1867 still forms the basis of our knowledge of certain hand functions controlled by the ulnar nerve

PREVIOUS INVESTIGATIONS

Later authors base their investigations largely on Duchenne s work of 1867 The expansion of our knowledge of the clinical picture of ulnar paralysis since then is a result of details reported by individual authors

SYMPTOMS AND SIGNS

Thus most symptoms and signs have with time been described some of them are known by the names of the authors who described them Table 13 gives some of the symptoms and signs arranged in chronological order The Table can be used for diagnosis of the level of ulnar injury in zones III and IV It can also be used as a guide in the investigation of cases in which anomalous innervation is suspected

Of those who have studied the deformation in ulnar paralysis mention should also be made of af Björkesten (1946) Bruner (1948) Littler (1952), Vallone (1953) Eyler Markee (1954) and Zancolli (1957)

It has long been known that the volar side of the little finger and the ulnar aspect of the volar side of the ring finger are desensibilised in ulnar lesions (Head and Sherren 1920) It is important to ascertain whether the sensibility of the dorsal side of the little finger has been lost in injury to the lower part of the lower arm If the sensibility of the dorsal aspect of the little finger is good and there is loss of sensibility of the little finger on the volar side and half of the ring finger with total intrinsic paralysis there is reason to assume that the injury lies distal to the origin of the ramus dorsalis manus Of authors who have discussed the pattern of sensibility of the ulnar nerve mention might be made of Stopford (1918) and Foerster (1929) In a few per cent of Stopford s (1918) cases the ulnar nerve supplied the entire ring finger and the ulnar half of the middle finger

The type of ulnar paralysis depends on the zone in which the nerve is injured and where in that zone It was therefore considered justified to divide the description of ulnar paralysis according to zones c. f Fig 1

Symptoms and signs of ulnar paralysis in zone I

Paralysis of the flexor carpi ulnaris and flexor digitorum profundus IV—V cause atrophy of these muscles reflected by change in profile of the proxi

Table 13 Symptoms and signs in ulnar nerve paralysis

Author	Year	Symptoms and signs
Duchenne	1867	Clawing of the ring and little fingers Little finger cannot be adducted to the ring finger Inability to play high notes on the violin Reason Flexor carpi ulnaris and opponens digiti quinti paralytic together with loss of sensibility of the little finger
Jeanne	1915	Hyperextension of the MP joint of the thumb in pinching grip Jeanne's sign (Fig 22)
Froment	1915	Pronounced flexion of IP joint of the thumb on adduction towards index finger Froment's sign (Signe du Journal) (Fig 23)
Masse	1916	Flattened metacarpal arch
Andre Thomas	1917	Wrist tends to fall into volar flexion on action of long finger extensors (Fig 24)
Pollock	1919	Inability to flex distal phalanx on dig V
Pitres Testut	1925	Transverse diameter of hand decreased Radial ulnar abduction of dig III in MP joint III impossible *Inability to shape the hand to a cone (Fig 25)*
Wartenberg	1939	Inability to adduct the extended little finger to the extended ring finger Wartenberg's sign (Fig 26)
Sunderland	1944	Inability to rotate oppose supinate little finger towards thumb Sunderland's sign
Fay	1954	Inability of thumb to reach little finger in true opposition (Probably misinterpretation of author because little finger cannot always reach thumb in paralysis of the opponens of little finger)
Bunnell	1956	The thumb no longer pinches against the index finger to make a good O
Egawa	1959	Inability of the flexed long finger to abduct radially ulnarly and to rotate in MP joint III
Mumenthaler	1961	On abduction of the little finger against resistance no normal dimple in hypothenar because of paresis of palmaris brevis musculature



Fig 22 Jeanne s sign

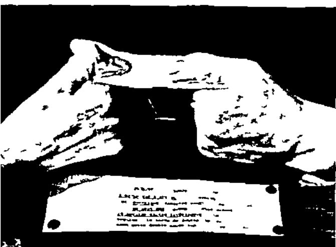


Fig 23 Froment s sign Model made by J Froment now in possession of Professor R Froment Lyon Photograph taken with kind permission of the owner

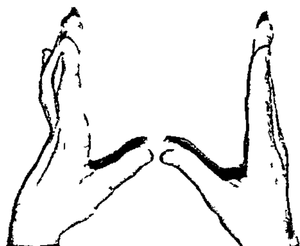


Fig 24 Andre Thomas s sign

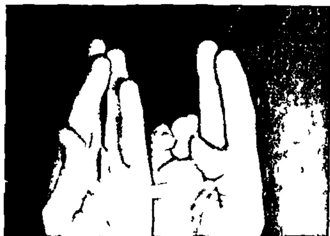


Fig 25 The Pitres Testut sign

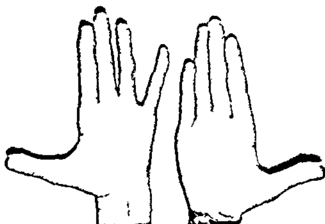


Fig 26 Wartenberg s sign

mal volar ulnar part of the lower arm Volar flexion of the wrist about the *radio ulnar axis is thereby weakened and when making a fist the pulps* of the ring finger and little finger lands in a more proximal area of the *palm The final phase of the grip is thereby weakened around a handle* When the hand is palm down the little finger cannot scratch the edge of *the table Since all interossei and hypothenar muscles 2—3 ulnar lumbri* cals adductor pollicis and to a varying extent flexor pollicis brevis are *thrown out of action the typical signs of ulnar paralysis naturally* appear It should be observed that the clawing is only moderate and often only *slight* because *the flexor digitorum* profundus IV and V are paralytic

Paralysis of flexor carpi ulnaris limits ulnar abduction about the dorso-volar axis of the wrist and makes it difficult to work with a hammer or an axe for example

The entire little finger and the ulnar part of the ring finger have lost their sensibility The sudomotor function also ceases in these areas (Moberg 1958) and the skin gradually becomes thin and atrophic. Trophic ulcers" are typical in total ulnar lesions They should be regarded as sequelae after loss of protection sensibility and not as trophic"

Symptoms and signs of paralysis of ulnar nerve in zone II

Two types of clawing can occur depending on the level of total ulnar injury in this zone If the injury is high little or moderate clawing occurs If the injury is below the origin of the motor branches of the flexor digitorum profundus IV—V clawing is more severe Sometimes there is no hyperextension of the metacarpo-phalangeal joints IV and V because fibrocartilago volaris in these joints will not allow it (Zancolli 1957) Loss of motor activity of the hand has the same effect as injury to the ulnar nerve in zone I

In the investigation of the level of the injury the sensibility of the dorsal side of the little finger should be tested (see above)

Symptoms and signs of paralysis of the ulnar nerve in zone III

The possibilities of ascertaining the level of ulnar injury in zone III are fairly good If sensibility is adequate in the little and ring finger as well as the motor activity of palmaris brevis but other motor functions distal thereto are lost there is reason to suspect total injury of ramus profundus Wartenberg s Sunderland s Egawa s and Froment s signs are positive The patient cannot form the finger to a cone The pinch grip is broken down In injury at the transition between zone III and IV Sunderland s sign will be negative but Wartenberg s sign will be positive as will other signs of paralysis of the distal ulnar nerve

Symptoms and signs of paralysis of ulnar nerve zone IV

Here too it is fairly easy to ascertain the level of the injury If in table 1 injury should be presented between the nerves 21 and 22 it would cause the following picture Sunderland s sign would be negative Wartenberg s negative Egawa s sign positive and the other signs of paralysis of ulnar nerve distal to this level would be positive Another example in a relatively distal ulnar injury the long finger can be abducted with considerable strength in ulnar direction but not radially and the index finger cannot be adducted with strength towards the long finger The injury is then most likely just distal to the origin of the nerve supplying the 3rd dorsal inter

osseous Egawa s sign is then no longer completely positive Froment s sign is however positive and the pinching grip is disintegrated Jeanne s sign is positive

In the analysis of ulnar injuries distal to zone IV the behaviour of interosseus dorsalis I and adductor pollicis must be studied carefully Inability of the index finger to be abducted radially in a particular injury where palmar adduction of the thumb is normal suggests a lesion of the deep ulnar branch distal to the origin of the branches supplying the transverse and oblique heads of the adductor pollicis

By classifying the nerve injuries according to these zones it is often possible to ascertain the level at which the ulnar nerve is damaged These examinations can be refined by anatomically correct electromyographic examination and by careful examination of the strength of individual muscle movements (see below)

It is thus clear that certain quick methods for testing the function of the ulnar nerve may be misleading Some examples are given below

1 Spreading of the 4 ulnar fingers does not mean that ulnar function is intact (Galenus Duchenne 1867)

2 Radial abduction of the index finger therefore does not mean that the ulnar function is intact either

3 Ulnar abduction of the index finger need not mean that the function of interosseus volaris I is intact (Extensor dig com II Duchenne 1867)

4 Some decrease of the residual strength of adduction of the thumb need not mean partial ulnar injury (Fick 1845 Extensor pollicis adducens)

These so called trick movements can instead mislead and trick the examiner

WHAT IS THE DISABILITY

af Bjorkesten (1946) appears to be one of the few who have systematically tried to assess the disability of persons with total ulnar paralysis Otherwise the literature simply says that the hand becomes weak and awkward and that clawing is common The disability due to loss of sensibility of the entire little finger and half of the ring finger is often belittled Loss of sensibility is thus classified as inconvenient but hardly as appreciably impairing the use of the hand

The loss of extension of the interphalangeal joints with increasing atrophy can with time result in contractures which impair hand function still more The hand may become so weak that it can no longer grip or hold things properly the patient may find it difficult to write and many

Part V On blocking of nerves

Chapter IX On blocking of nerves

HISTORICAL

According to Collins (1960) Halstead appears to be the father of nerve blocking (1884) but it was apparently Frank (1892) who coined the term nerve blocking Frank assigned the procedure to a physiologic nerve section

Interest in diagnostic problems bearing on nerve injuries increased during the world war II Highet (1942) was one of the first to use diagnostic nerve blocking He utilised this method in a series of more than 50 cases in an investigation for anomalous innervation of muscles and for studying disturbed sensibility in partial and total peripheral nerve injuries

PREVIOUS INVESTIGATIONS

Intraneural versus extraneural block

Highet (1942) induced the block intraneurally Other authors who used this technique are Chase Brandom Macomber and Wang (1959) Dhuner Edshage and Wilhelm (1960) Albert and Lofstrom (1961) and Moore (1961) According to Moore nerve blocking is a measure to obtain reversible chemical section of the nerve

Bonica (1959) and Collins (1960) advice against intraneural blocks Bonica claims that it involves a risk of socalled post injection neuropathy but believes that sensibility disturbances pareses or disturbances of the autonomic nervous system after nerve blocking with local anesthetics are rare Such neuropathies according to him are due to mechanical injury by the tip of a needle This view is incompatible with Matson s (1950) report of the treatment of nerve injury following erroneous injection of antibiotics He believes that it is the antibiotics that are toxic for the nerve and that the penetration of the nerve by the needle per se is not dangerous Collin s (1960) who defines nerve blocking as a procedure in which the nerve conduction is blocked and in which loss of function is reversible believes that intraneural block should be avoided but at the same time says that one can very well inject when the patient feels paresthesia This

statement that a patient experiences paresthesia probably means that the needle is nevertheless within the nerve

Other authors who have used nerve blocking for different purposes are Murphey Kirklin and Finlayson (1946) Braithwaite, Channell Moore and Willis (1948) Clifton (1948) Rowntree (1949) Haymaker and Woodhall (1953) Goldner (1953) Eyler and Markee 1954), Moberg (1958) and Egawa (1959) They do not however say whether nerve blocking should be induced intraneurally or not

Nerve blocking has been used for scientific and practical purposes Several authors used nerve blocking as an instrument for investigating troublesome problems in suspected anomalous innervation Dhuner et al (1960) and Albert and Lofström (1961) have used nerve blocking to test the effect of different anaesthetic media Several of the authors have studied the effect of blocking of the ulnar nerve

Criteria and evidence of total nerve block

Various methods have been used by different authors to find evidence of a total nerve block in human being Highet (1942) for example used the 4 criteria

1 Complete vaso-dilatation
2 Anhidrosis
3 Anesthesia and analgesia
4 Complete paralysis of the muscles supplied by the nerve distally to the level of the block

Various objective methods for testing anhidrosis are available Of known methods mention might be made of the iodine starch method (Minor 1928 Dole and Thaysen 1953) Moberg s ninhydrin printing test (1958) has also proved suitable

Technique for avoiding nerve injury in induction of nerve block

According to the literature complications after intraneural nerve block appear to be rare

It is true that Bonica (1959) stresses the risk of post injection neuro pathy following intraneural anesthesia No cases have been published in his work Dhuner *et al* (1960) reported no neurogenous injury demon strable by conventional neurological methods or by the ninhydrin method after 41 intraneural blocks Also Highet (1942) believed intraneural in jection of a local anesthetic to be safe

Moore (1961) gave a careful description of precautions to be observed before inducing nerve block A nerve block should thus be performed with great care and under sterile cautions All needles should be inspected be

fore use—the tips should be satisfactory Moore also emphasises the risk of the tip of the needle coming into contact with bone and thereby being hooked If the tip of the needle is hooked it can cause injury when withdrawn after injection If the above precautions are observed and only a reasonable amount of local anesthetic is injected intraneural block should be safe

ULNAR BLOCK BY AUTHORS METHOD

Technique

In the investigation of the residual capacity of the hand in ulnar paralysis it was decided to block the ulnar nerve intraneurally in the distal part of zone I 1 % Carbocain® without adrenalin was used In the beginning a fine needle (0 35 mm in diameter) was employed but a needle of this size soon proved too small to maintain the paresthesia for which reason a larger needle was then used (diameter 0 45 mm No 18 Injecta Sjuco) The local anesthetic was injected a few centimetres proximal to the sulcus nervi ulnaris It is indefensible to inject a local anesthetic into the oseo fibrous cubital channel (Feindel and Stratford 1958) because of the unavoidable subsequent oedema in the nerve after intraneural block Intraneural block was induced in the following way With the patient lying comfortably on his back on an examination table with the upper arm abduced and rotated outwards and the elbow flexed the ulnar nerve was palpated and gripped between my finger and thumb The skin was disinfected with alcohol The fine needle was inserted through the skin and at right angles into the nerve When the patient felt paresthesia down into the little finger 2—3 ml of 1 % Carbocain® without adrenalin was injected into the nerve Afterward 2—3 ml of the same anesthetic was deposited around the nerve at the same level Both before and after use of the needle the tip was drawn through a sterile compress in order to check that the tip was not hooked On no occasion in the 57 blocks (cf page 111) was any such hooking found

Author s criteria of completeness of intraneural block

The following criteria were used

1 Complete anhidrosis in the volar distal surface of the little finger
2 Vasodilatation in the ulnar part of the hand
3 Complete loss of sensibility of the little finger
4 Paralysis of muscles normally innervated in the ulnar nerve
5 The following signs should be positive
   a. Wartenberg s   c Egawa s
   b Sunderland s   d Froment s

6 Electromyographic evidence Supramaximal stimuli proximal to the block should produce no action potentials when surface electrodes were placed over the musculature of the interosseus dorsalis I and abductor digiti quinti while supramaximal stimulation distal to the site of injection produce a normal response

Criterion 1

Anhidrosis in the distal volar surface of the little finger was assessed objectively with the ninhydrin printing test (Moberg 1958) quantitated in the way used by Önne (1962) The active surface of the paper in the ninhydrin printing test was 19 6 mm (a circular area 5 mm in diameter) A series of impressions were made beginning immediately after the injection The finger was said to be anhidrotic when no sweat spots were demonstrable

Criterion 2

Vasodilatation was recorded partly by the subject himself who reported that the ulnar part of the hand felt warm after the block The examiner controlled the patient s statement by comparing the warmth of the ulnar and of the radial part of the subject s hand (Skin temperature was measured in only 1 case It was case ♂ 8 where the skin temperature in the hypothenar region before the blockade was 34 0° C and 36 6° C after the block)

Criterion 3

Loss of sensibility was said to be complete when the patient no longer felt a hard pinch of the pulp of the little finger Even protective sensibility had thus disappeared Moberg (1958) has shown that after nerve block anhidrosis and loss of sensibility occur simultaneously A ninhydrin test without spots of sweat was therefore taken as a sign of total loss of sensibility

Criterion 4

Paralysis of flexor carpi ulnaris and flexor dig com V was demonstrated clinically As to the testing of the intrinsic musculature see below

Criterion 5

a *A positive Wartenberg s* sign (1953) means that the abducted and extended little finger can no longer be actively adducted to the ring finger

b *Sunderland s sign* (1944) was regarded as positive when the patient could no longer rotate and supine the flexed little finger towards the the thumb in opposition Now and then the little finger passed the radial side of the thumb so that the tactile surfaces of the thumb and little finger could never contact to form grip The little finger could never reach the thumb in proper opposition after ulnar neural block that the distal phalanx of the little finger was in line with the distal phalanx of the thumb In stead there was a more or less pronounced radial open angle between the distal phalanges of the thumb and little finger The smaller the radial open angle the smaller the opposition supination of dig V If Sunderland s sign is positive there is also an absence of hypothenar elevation which is due to loss of function of opponens dig V decreased range of flexion of MP joint V and predominance of long extensors over the metacarpo-phalangeal joints of the little finger (clawing)

c *Egawa s sign* Egawa (1959) showed that the flexed long finger can no longer pro supinate in the palm Then the long finger can not move its tactile surface on the base of the thenar eminence in ulnar radial ulnar direction Egawa s sign is due of course to loss of function of the 2nd and 3rd interossei In the present investigation these were also tested by allowing the patient to extend the 4 ulnar fingers and on request to try to actively abduct the extend long finger radially and ulnarly

d *Froment s sign* This sign was tested according to Froment s original paper in 1915 The subject was requested to hold a disk between the thumb and index finger and requested to draw the hands from each other with the result that the distal phalanx of the thumb on the paralysed side flexed Now and then supination of the thumb occurred and sometimes pronation What was registered was above all flexion of the distal joint of the thumb On the healthy side the patient could hold the distal joint of the thumb extended

Criterion 6

Electromyographic evidence of completeness of intraneural block distal in one I

A Standard EMG investigation

It was considered necessary to produce also electromyographic evidence of the completeness of the block The method used was based largely on the paper of Hodes Larrabee and German (1948) These authors used their technique for registering the conduction velocity of motoraxons This method was used by me to show that not even after stimulation with supra

maximal stimuli proximally to the block could any action potentials be demonstrated in the musculature of the abductor digiti quinti and interosseus dorsalis I

The ulnar nerve was stimulated with a stimulator (Multistim DISA 13 G 04) and with bipolar surface electrodes Fig 27 The interelectrode distance was about 25 mm Rectangular impulses of 1 0 msec duration were used The potential of the muscle response was taken up by surface electrodes made of tin plates 12×6 mm One electrode was placed over the muscle and one over the tendon of the muscle The abductor digiti quinti and interosseus dorsalis I were used as receptors The potentials were recorded with an electromyograph (DISA 13 A 69) Single sweeps were used with a sweep velocity of 1 or 2 msec. The cathode ray sweep was triggered off by a prepulse from the stimulator a marking pulse indicated the instant of stimulation

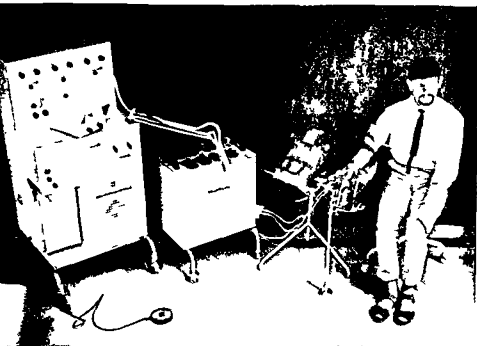
Before the block was induced the conduction velocity of the ulnar nerve was measured The ulnar nerve was stimulated somewhat proximal to the sulcus nervi ulnaris The lowest strength necessary to produce a response was determined This intensity was increased by 100 % and was thereby regarded as supramaximal

The surface electrodes were kept in position and the subject was given an intraneural block in the ulnar nerve distally in zone I *i e* just proximal to the sulcus nervi ulnaris Supramaximal stimuli were then given proximal to the block and high sensitivity (10 μV/mm) was used

When no action potentials could be seen the block was regarded to be complete — cf Figs 37 38

Certain objections can be raised against this technique Thus it may be questioned whether needle electrodes were not used to take up action potentials from abductor digiti quinti and interosseus dorsalis I The reason why needle electrodes were not used was that the subject could then readily feel pain when measuring certain grips in which interosseus dorsalis I and abductor digiti quinti take part Insertion of these needles can cause haematomas Another objection is that needle electrodes take up a relatively smaller volume of activity from the actual muscle while surface electrodes take up a relatively larger volume of activity from the actual muscle A third objection is that the needle electrodes can slip out on examination of the grip directly after the block A standardised position of the needle electrodes could therefore be jeopardized. In view of the above objections it was decided to use surface electrodes over the muscles in question It was however useful in certain special cases to use needle electrodes in examinations for voluntary maximal contractions (cf chapter X Martin Gruber anastomoses)

As to the skin impedance no attempts were made to measure it When



?7 Set up for demonstrating complete ulnar nerve block

using skin electrode stimulation the skin impedance should presumably be the same before and after induction of the block The skin was not examined for any change of impedance due to the vaso-constrictive effect of Carbocain® 1 % without adrenalin

B More rigorous EMG test of completeness of intraneural block in distal part of zone I

A more refined method for demonstrating completeness of intraneural block would be to stimulate the nerve proximally to the level of anesthesia by percutaneously inserted needles placed as near the nerve as possible A test was carried out on one 27 year old male medical student The conduction velocity of the ulnar nerve was determined The nerve was stimulated by the juxtaneural needle electrodes (distance 3 cm from one another) and the action potentials were picked up with needle electrodes in m abductor digiti quinti and m. interosseus dorsalis I The site of nerve stimulation was somewhat proximal to the sulcus nervi ulnaris

3 ml of 1 % Carbocain® without adrenalin was injected intraneurally in the ulnar nerve and 2 ml extraneurally

Nine minutes later the ulnar nerve was stimulated again as before and

a new recording was performed from the above mentioned muscles with the needle electrodes The duration of stimulation was 2 msec The stimulation strength was supramaximal (17 volt) The sensitivity of the electromyograph was set at 7 5 μV/mm Action potentials could not be demonstrated in the muscles although several electrode positions were used This was taken as a proof that the block was complete but it could also be explained as a diminution of the conduction velocity of the action potentials

Conduction velocity decreases in a nerve which is anesthetised (Rud 1961) In order to check that the finding did not mask a decrease in conduction velocity, the following experiment was performed The ulnar nerve was stimulated as before By using a second stimulator of the type Multistim (Disa 13 G 04) which was triggered by the first stimulator the sweep of the EMG apparatus could be delayed Thereby a maximum range of 300 msec after the onset of the stimulation could be covered The maximum conduction velocity for the ulnar nerve is 65—68 m/sec (Hodes Larrabee and German 1948 Moritz 1963) The conduction velocity varies with the diameter of the nerve and the lowest velocity is roughly 3 m/sec If half of this value is considered the maximum permissible decrease in conduction velocity before block occurs this will give us 1 5 m sec over a distance of 4 5 cm which is estimated as the maximum distance of the nerve subjected to the influence of the local anesthetic This is an addition to the transmission time of 30 msec The conduction velocity in the nerve is normal distally to the anesthetized portion (Rud 1961) Therefore 150 msec must be added to the transmission time corresponding to 45 cm of nerve conduction at 3 m/sec If a few msecs are allowed for synaptic transmission and propagation within the muscle to the electrodes we are able to say that we have to look for potentials within the range of 180—185 msec after the onset of stimulation

The described experiment covers this range with a good margin

SUMMARY

Published techniques of blocking nerves with local anesthetics are discussed Thus there is controversy concerning intra versus extraneural block techniques

Criteria of total nerve block are given by Highet (1942) The present author has used these criteria but thought there could be more rigorous proofs of a total ulnar nerve block Therefore an electromyographic technique was added This was based on the work by Hodes Larrabee and German (1948) and with a more refined technique it was shown by the present author that it is possible to obtain an electromyographically total ulnar block efter intraneural injection of a local anesthetic 1 % Carbocain® without adrenalin

Part VI Evaluation of some residual functions of the hand in high ulnar block

Chapter X Evalution of some functions of the hand in high ulnar block

AUTHORS SERIES

COMPOSITION OF THE MATERIAL

The material consisted of 40 volunteers 30 male medical students and 10 female students of physiotherapy

Of the males 28 were 19—24 years of age and 2 were 26 years Of the females 8 were between 20 and 23 years one 24 and one 25 years The age distribution of the series was thus very similar to that of the controls None of the 40 volunteers had ever sustained injury to the hand tested and none of them had had any diseases of the central or peripheral nervous system

In order to form a personal opinion of the effect of ulnar paralysis the author participated in the trial as No 41

Since the induction of ulnar block sometimes failed and since special investigations were sometimes necessary the total number of blocks induced was 57

PERFORMANCE OF THE INVESTIGATION

The 41 persons in whom ulnar block was induced were subjected to the same examination on day 1 as the controls This examination was repeated on day 7 Ulnar block was induced immediately after this examination and the subjects were re examined on day 13

Twenty five male students (♂ 1—25) 10 female students (♀ 1—10) and the author (♂ 41) were examined in this way

A small group of 5 students (♂ I—V) were examined daily for 13 days In these 5 ulnar block was induced on day 7

The course of the examination in the various groups is given in Table 14

The better hand was studied One of the males but none of the females was left handed

As in the examination of the controls the temperature and the relative humidity of the examination room were measured at every examination

Table 14 Course of the investigation

Day of investigation	♂ 1—5 N = 5	♂ 1—25 N = 25	♀ 1—10 N = 10	Author N = 1	Σ
1	×	×	×	×	41
2	×				5
3	×				5
4	×				5
5					5
6	×				5
7	×	×	×	×	41
7 Block	×	×	×	×	41
8	×				5
9	×				5
10	×				5
11	×				5
12	×				5
13	×	×	×	×	41

BLOCKING OF THE ULNAR NERVE

After basic examination on day 7 the ulnar nerve was blocked intraneurally a few centimetres proximal to the sulcus nervi ulnaris. Carbocain® 1 % without adrenalin was used. This level was chosen for the following reasons:

1. At this level the nerve has not yet given off any motor branches.
2. This level is proximal to Martin-Gruber anastomosis, if present, in the lower arm.
3. At this level the ulnar nerve is so far from the median nerve that the latter is less likely to be affected by the local anesthetic.
4. Because of the risk of oedema after intraneural injection. The local anesthetic should therefore not be deposited in sulcus nervi ulnaris but proximal to it. At the level of and in the sulcus nervi ulnaris the nerve is in an osseofibrous tunnel (so-called cubital tunnel—Seindal and Stratford 1948).
5. This is a common level of clinical injury.
6. The nerve here is readily accessible for injection and for electrical stimulation.
7. Block at this level, when properly performed, is safe.

The technique described in Chapter IX was used to prove the completeness of the block Not until after this completeness was proved was the subjects arm and hand placed in the examination bridge and examined in the way described above Ninhydrin printing tests were taken immediately before this examination

EXAMINATION METHODS

1 The strength of the hand was measured with *Collin s dynamometer* before and after examination with the author s dynamometer
2 *The subject s hand was then placed in the examination bridge in the* way described for the control group in Chapter VII The following values were thus determined with the *author s dynamometer*
   a The strength of pinching grip
   b The strength of palmar adduction of the thumb
   c The strength of radial abduction of the index finger
   d The strength of adduction in the 2nd interspace
   e The strength of adduction in the 4th interspace
   f The strength of ulnar abduction of the little finger

Here as in the control series the subjects were unaware of the values recorded Jerky movements and tests in which the subjects obviously over exerted themselves were not accepted

3 Then followed the *picking up test* and the *pin test*
4 *Sensibility* was assessed with the ninhydrin printing test immediately after these measurements
5 *Subject s auto investigation* After these examinations each subject was given two paper strips and requested to take ninhydrin impressions
   a When he began to feel paresthesia of the little finger The time of onset of such paresthesia was noted
   b When he thought that he had recovered normal sensibility of the finger He should also here note the time

The subjects were also requested to outline the area of loss of sensibility on the volar and dorsal aspects of the hand after induction of ulnar block. This test was crude because only the sense modality of touch was studied

The subject was requested to note the time when it was again possible for him to adduct the extended little finger towards the ring finger *i e* when Wartenberg s sign had become negative Finally he was requested to state the time of recovery of the normal pinching grip *i e* when the thumb and index finger could form a firm normal round 0

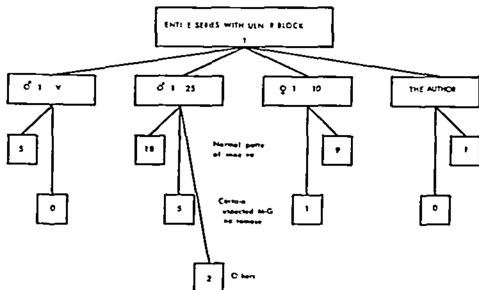


Fig 28

The subjects were also requested to describe in their own words what they thought was difficult to perform after they had come home to their ordinary environments with ulnar paralysis

RESULTS

Groups

The series was divided into 3 groups according to the measurements noted during ulnar paralysis (Fig 28)

a The largest group was homogeneous and the values obtained in high ulnar block suggested that paralysis of the muscles conventionally believed to be supplied by the ulnar nerve were paralysed In this group the *innervation pattern* was regarded as *normal*

b In this group the values obtained were far too high Paralysis was not complete Some of them did not fill the criteria of complete block (Chapter IX) Certain electromyographic signs suggested persistent function of the nerve in 14 of the subjects A second attempt to induce ulnar block in these 14 subjects proved successful in 6 of them They were then transferred to group 1 This left 8 subjects with a varying degree of paresis Of these 8 one (♂ 8) appeared to have complete ulnar paralysis except regarding the pinching grip — this was probably due to a measuring error in that he

always pulled the index finger in flexion and thereby obtained a high pinch value In another subject the first injection failed to produce ulnar block and the subject refused a second attempt (Case ♂ 3—transferred to group others) A further subject (Case ♂ 5 group others) may have had a Riche Cannieu anastomosis but also here the injection failed to produce complete ulnar block even in a second attempt and the subject refused a third The remaining 6 subjects were examined for Martin Gruber anastomosis These subjects were assigned to a special group called *certain or suspected Martin Gruber anastomoses*

c *Others* cases ♂ 3 and ♂ 5 see above

Tables 30—41 at the end of the book give a statistical analysis of the measurements made on days 1 7 and 13 as well as in ulnar block As for group ♂ 1—25 only 15—18 subjects are included in the tables The reason for this is given in Table 15

Error of method

The error of the method — ε — is expressed in degrees of the dynamometer dial and is calculated according to the formula

$$\varepsilon = \sqrt{\frac{\Sigma\Sigma(X_j - M)}{N(n-1)}}$$

The symbols are the same as those used in the discussion of the error of the method in the control serie (Chapter VII) The error of the method reflects the reliability of the measuring method the values are given in Table 16 The error of the method thus implies for example that for pinching grip with the wrist at an angle of +30 the error with 68 % certainty is ±6 degrees on the scale If a reliability of 95 % or 99 7 % be chosen ε must be doubled or trebled The table also gives the error of the method in per cent of the actual mean in a given test.

In the discussion of the error of the method the following variables must be considered

1 The difficulty the examiner has in reading the value on the dynamometer dial
2 The ability of the subject to maintain a constant pressure in the end phase of isometric muscle contraction i e the degree of quivering of the indicator The error of the method must of course be greater in a group with ulnar paralysis than in a control group In ulnar paralysis there is marked incoordination of practically all grips and movements In view of the above mentioned variables the error of the method was low and acceptable

Standard Deviation

In the statistical treatment of the data obtained in the above tests with the dynamometer the median value was used Three measurements were made in each test. The means of the values were calculated as the arithmetic mean of the median

Table 15 Reasons for exclusion of certain subjects in group ♂ 1—25

	PINCH	ADD POLL	ABD II	ADD II 1	ADD IV 1	ABD V	COLLIN
Martin Gruber anastomosis Subjects ♂ 2 9, 14 21 25	5	5	5	5	5	5	5
Unsuccessful blocks Riche Cannieu anastomosis? Subjects ♂ 3 5	2	2	2	2	2	2	2
Later block successful but subject not completely measured Subjects ♂ 4 8 24	(2)	(2)	(2)	2	3	2	2
Faulty performance Subject ♂ 8	1	—	—	—	—	—	—
Remainder	17—15	18—16	18—16	16	15	16	16

Table 16 Error of method — ε — in block group (♂ 1—25 and ♀ 1—10)

Examination	Angle of wrist joint	Angle of MP joint	ε	$100\frac{\varepsilon}{M}$	Block values N	M	s
Pinching grip							
♂	+30	—	6	15	17	39	12
♀			4	14	9	30	11
Palmar adduction of thumb							
♂	±0	—	5	20	18	27	9
♀			3	13	9	25	12
Radial abduction of index finger							
♂	±0	180	4	11	18	34	17
♀			4	15	9	25	9
Adduction in second interspace							
♂	±0	180	5	16	15	28	12
♀			3	16	9	22	9
Adduction in fourth interspace							
♂	±0	180	—	—	16	0	0
♀			—	—	9	0	0
Ulnar abduction of little finger							
♂	±0	180	2	12	17	14	10
♀			2	27	9	9	6

values of the 3 measurements for each subject The standard deviation — s — was calculated according to the formula

$$s = \sqrt{\frac{\Sigma(X_i - M)}{N-1}}$$ where

X = measured median value for the subject
M = arithmetic mean of the median values of the 3 measurements for each subject
N = number of subjects

I GROUP WITH NORMAL PATTERN OF INNERVATION

RECORDINGS WITH AUTHORS DYNAMOMETER

General

1 On day 1 the basic values noted for all 40 subjects were largely the same as those noted in the control group on that day The group of subjects was therefore representative

2 On day 13 the values noted in the experimental series were somewhat higher in certain tests (*inter alia* pinching grip palmar adduction of the thumb and radial abduction of the index finger) but this was only in group ♂ I—V Here then there was a certain training effect This could be detected already before day 7 In group ♂ 1—25 and ♀ 1—10 there was no such increase of the values recorded on day 13

3 Some of the female subjects showed somewhat lower values in some of the tests on day 13 These subjects were re examined 6 months later and then the values were comparable to those noted on day 1

Below and in the discussion of the values noted during ulnar paralysis after ulnar block each test is dealt with separately Table 17 gives mean values in kilograms in ulnar nerve block For details see Tables 30—41 at the end of the book

Pinching grip

The measurements made during ulnar paralysis did not vary with the de gree of flexion or extension of the wrist about the radio ulnar axis This applies to all three groups ♂ I—V ♂ 1—25 and ♀ 1—10

Palmar adduction of the thumb

The values noted during ulnar paralysis showed a slight tendency to fall with increasing flexion of the wrist (♂ 1—25 and ♂ I—V) This ten dency was however not seen in group ♀ 1—10

When the wrist was flexed more than —50°, the values noted in special subjects decreased continuously towards nil This phenomenon is discussed later in this Chapter pages 142—148

Radial abduction of the index finger

The values noted during paralysis seemed to be higher in group ♂ I—V than in group ♂ 1—25 This was regarded as a training effect which was noted already before day 7 It might have been an increase in the strength of the extrinsic musculature and then particularly of the extensor digi torum communis II

Table 17 Mean values in kg for block group (♂ 1—25 and ♀ 1—10)

	PINCH	ADD POLL	ABD II	ADD II 1	ADD IV 1	ABD V
Position of *wrist joint*	+30	±0	±0	±0	±0	±0
Position of MP joint	—	—	180	180	180	180
♂	0 85	0 6	0 75	0 61	0	0 35
♀	0 65	0 6	0 55	0 5	0	0 2

In the group ♂ I—V there was a slight difference between the values measured during paralysis at an angle of the wrist at + 30 and — 30 No statistically significant difference was found in the groups ♂ 1—25 and ♀ 1—10 No explanation can be offered for this discrepancy

Adduction strength in the 2nd interspace

Normally the adduction strength in the 2nd interspace is greater when the metacarpo phalangeal joints are flexed than when extended The reason for this difference has been discussed previously in the description of the examination of the control group Also during ulnar paralysis the values were higher when the metacarpo phalangeal joints II—III were flexed than when they were extended This is probably because the abducting effect of the long extensors is less when the metacarpophalangeal joints are flexed The long flexors probably contribute to the increased strength of adduction when the metacarpo-phalangeal joints are flexed

This difference between the values noted when the metacarpo phalangeal joints II—III are flexed and extended applies to all groups (♂ I—V ♂ 1—25 ♀ 1—10)

Adduction strength in 4th interspace

In ulnar paralysis the little finger could of course not be adducted to the ring finger The values are therefore marked as 0 This loss of adduction of the little finger is due to paralysis of the 3rd volar interosseous (Wartenberg s sign positive)

Table 18 Residual strength in percent in high ulnar block — Approx values

Test	Group	Position of wrist or MP joint						
		+70	+50	+30	±0	—30	—50	180
PINCH	♂ I—V	21	15	16	15	16		
	♂ 1—25	20	14	17	18	18		
	♀ 1—10	27	19	17	11	19		
ADD POLL	♂ I—V		29	22	25	18	16	
	♂ 1—25		24	18	18	15	13	
	♀ 1—10		27	23	22	22	21	
ABD II	♂ I—V			24	20	16		
	♂ 1—25			14	14	12		
	♀ 1—10			15	13	13		
ADD II i	♂ I—V							19
	♂ 1—25							27
	♀ 1—10							24
ADD IV i	♂ I—V							0
	♂ 1—25							0
	♀ 1—10							0
ABD V	♂ I—V							17
	♂ 1—25							14
	♀ 1—10							11

Ulnar abduction of little finger

The values noted for the 2 positions of the metacarpo-phalangeal joint V (180° and 120°) were largely the same in the 3 groups ♂ I—V ♂ 1—25 and ♀ 1—10 When the metacarpo-phalangeal joint was extended the means for these 3 groups were 16±9 14±10 and 9±6 on the scale The strength of ulnar abduction of the little finger when the metacarpo-phalangeal joint was flexed was low and was mostly measured as 0 This may be explained in the following way The extensor digiti quinti proprius and extensor digitorum communis V are abducting in ulnar direction when the *metacarpo-phalangeal joint V is in extended position On flexion of the* metacarpo-phalangeal joint V the effect of the long extensors is weakened In addition the collateral ligaments are tightened It is therefore not surprising that the strength of ulnar abduction of the little finger decreases with increasing flexion of the metacarpo phalangeal joint V in ulnar paralysis

Residual amount of strength in per cent is given for each test i Table 18

Table 19 Residual strength in high ulnar block Collin s dynamometer

Group	N	Normal value kgf	Block value kgf	Residual capacity in % approx
♂ I–V	5	40±9	9±6	22
♂ 1–25	16	45±11	13±7	29
♀ 1–10	9	30±6	8±4	27

RESIDUAL CAPACITY MEASURED WITH COLLIN S DYNAMOMETER

Thirty subjects of group ♂ I—V ♂ 1—25 and ♀ 1—10 were tested regarding their ability to perform a power grip around Collin s dynamometer with the wrist in 30 dorsal extension Standing with the upper and lower arm extended along the side of the body the subject was instructed to grip the dynamometer as hard as he could During ulnar block group ♂ I—V had a residual capacity of 9±6 kgf group ♂ 1—25 13±7 kgf and group ♀ 1—10 8±4 kgf (Table 19) The residual capacity measured in this way was 22—29 % of the normal

RESIDUAL CAPACITY MEASURED WITH PICKING UP TEST

In Moberg s picking up test (1958) the patient picks up small objects from the table and places them in a receptacle with and without his eyes blind folded During the test the examiner watches the way the patient grips the objects Moberg described the test as a refined test where the sensibility governs the grip The main purpose of the picking up test according to Moberg (1958) is to examine the grip function of patients with impaired or complete loss of sensibility of the median nerve

The test was however considered useful in the present investigation of residual capacity of the function of the hand in persons with ulnar nerve block To enable statistical analysis the test was quantitated and performed under standardised conditions The subject was instructed to pick up a predetermined number of objects from a smooth surface and place them in a receptacle The time was noted from the moment the subject touched the first object until he had dropped the last object in the receptacle Each subject performed the test 3 times with the eyes blind folded and 3 times without

Table 20 Picking up test Group ♂ 1—25 and ♀ 1—10
Figures in seconds

Sex	Day	Performance					
		Seeing			Blindfolded		
		N	M	s	N	M	s
♂	1	16	6 3	0 7	16	17 2	3 2
	7 A	16	6 4	0 9	16	14 7	2 6
	7 B	14	9 0	1 8	14	25 3	5 8
	13	16	6 4	0 8	16	15 0	2 8
♀	1	9	6 0	0 5	9	16 5	3 2
	7 A	9	5 9	0 5	9	14 5	2 8
	7 B	9	10 [illegible]	1 9	9	30 0	8 5
	13	9	6 0	0 6	9	14 2	1 7

Table 21 Picking up test

Performance and comparison	Lengthening factor ♂	♀
Seeing Blocked versus not blocked	1 4	1 8
Blindfolded Blocked versus not blocked	1 7	2 1
Blocked Blindfolded versus seeing	2 8	2 9
Blocked and *blindfolded* versus *not blocked* and *seeing*	4 0	5 1

Material

The original controls were not tested with this test Instead 25 subjects were tested before induction of ulnar block and served as their own controls The picking up test was studied in 16 male and 9 female students

Results

The times noted for the females and males when seeing were 6 3±0 7 and 6 0±0 5 seconds respectively and when blindfolded 17 2±3 2 and 16 5±3 2 seconds respectively

Tables 20 and 21 show that when blind folded the males and females required about 3 times as long a time for the picking up test as when they could see The lengthening time factor is here 2 8 and 2 9 respectively When the subjects were not blind folded the corresponding factors when the ulnar nerve was blocked and not blocked were 1 4 for the males and 1 8 for the females

When the subjects were blind folded the males required 1 7 and the females 2 1 times as long to perform the test when the nerve was blocked

The largest lengthening factors 4 0 and 5 1 were noted on comparison of the scores achieved by the subjects with ulnar block and blind folded compared with those noted when they were not blind folded and when the ulnar nerve was not blocked

Summary

The picking up test was standardised and timed The normal values were largely the same fo males and females — both when they were blind folded and when the re not When blind folded the subjects required about 3 times as lon erform the test Subjects blind folded and with ulnar block require times as long for the test as they did when seeing and before in of the block

The ability of on to perform certain precision movements in the dark with the ve blocked is thus severely impaired

RESIDUAI CITY MEASURED WITH IIN TEST

In the examir that part of the hand function tested with the picking up test a ubjects thus found it difficult to pick up a small needle from t d place it in the receptacle The picking up test was therefore ext include picking up a small needle from the table and piercin 10 mm thick with the needle Eight squares and 2 crosses should be pierced and the time required was noted The needle was held be the thumb and the tip of the index finger The head of the needle was mm in diameter The result of the test served as a base for evaluation o the patient s capacity to perform a precision grip with preserved sensibility Each subject performed the test three times and the time required was noted and the median value was used for statistical evaluation

Material

Nineteen male and 9 female students

Results

The values varied within each group This could be explained by natural differences in the dexterity of the subjects The method proved less suitable but in testing the functional capacity of the hand in ulnar paralysis it revealed certain phenomena of interest

The method was unsuitable for statistical treatment The mean value for the males with ulnar nerve blocked varied between 16.5 ± 9.5 sec and 24 0 ± 22 6 sec (Normal 7 7 ± 2 2 sec.)

With the ulnar nerve blocked the mean value found for the female students was 12 7 ± 6 9 sec (Normal 7 1 ± 1 4 sec)

The pinching grip of some of the students was too weak to enable them to force the needle through the paper The head of the needle slipped between the thumb and the tip of the index finger and fell onto the table

Summary

A method for testing the residual functional capacity of the hand in ulnar paralysis is described According to this test the person presses a needle through a sheet of paper of certain thickness Some of the subjects were so weak that they could not force the needle through the paper The scatter of the values obtained was too wide to allow statistical analysis

SYMPTOMS AND SIGNS

ONSET AND DISAPPEARANCE OF BLOCK

Loss of sensibility in high ulnar block

The loss of sensibility was complete in the distal volar part of the little finger in all 41 subjects and was demonstrated objectively by Moberg s ninhydrin printing test (Moberg 1958) here quantified

The loss of sensibility occurred 4 3 ± 2 6 min after induction of high ulnar block in 24 persons especially investigated for this purpose (Table 23)

The spread of the loss of sensibility in the volar and dorsal part of the hand is apparent from Table 22 The material consisted of 10 females and 22 males including the author In this series the subjects were requested to outline the area of loss of sensibility (sense modality of touch)

Results

A *Volar aspect*

1 Little finger

In all 32 subjects studied high ulnar block was followed by complete loss of sensibility on the ulnar and radial parts of the distal volar surface of the little finger

2 Ring finger

Thirty one of 32 subjects lost all sensibility of the distal ulnar volar surface of the ring finger Only 5 lost sensibility of the distal radial volar surface

3 Long finger

None of the 32 subjects lost sensibility on the volar aspect of the long finger Neither did any of them lose sensibility of the index finger or thumb

Table 22 Spread of loss of sensibility in high ulnar block

		Volar			Dorsal		
Finger Group	N	V U—R	IV U—R	III U—R	V U—R	IV U—R	III U—R
♂ 1—25	21	21—21	21—4	0—0	21—21	17—4	0—0
♀ 1—10	10	10—10	9—1	0—0	10—9	9—1	0—0
Author	1	1—1	1—0	0—0	1—1	1—0	0—0
Σ	32	32—32	31—5	0—0	32—31	27—5	0—0

Table 23 Onset of block

Investigation	N	$M_{minutes}$	s
1 Loss of sensibility	24	4 3	±2 6
2 *Wartenberg* sign pos	34	2 2	±1 6
3 *Sunderland* sign pos	33	2 3	±2 0
4 Pos hyperflex sign I—IV	23	2 3	
I—III	21	2 2	
I—II	22	4 5	

B *Dorsal aspect*

1 Little finger

All of the 32 subjects lost sensibility of the distal ulnar dorsal aspect of the little finger 31 of 32 lost sensibility of the distal radial dorsal aspect

2 Ring finger

27 of 32 subjects lost sensibility of the distal ulnar dorsal surface of the ring finger 5 of the distal radial dorsal side None of them lost sensibility of long finger index finger or of thumb

Discussion

According to some anatomical textbooks (Villiger Ludwig 1946 Monrad Krohn 1948 and v Lanz Wachsmuth 1959) loss of sensibility in patients with ulnar nerve injury affects the ulnar part of the distal dorsal aspect

of the long finger This opinion is not shared by *inter alia* Foerster (1929) and Chusid and McDonald (1962) In only 3—4 % of Stopford s series (1918) was there any sensibility of the ulnar nerve from the ulnar part of the long finger The results of the present investigation thus are in accord with those of Stopford (1918) Foerster (1929) and Chusid and McDonald (1962) The findings made in the present investigation did not confirm the assertion in some conventional anatomical textbooks regarding the sensibility of the dorsal part of the long finger

Muscular paralysis and onset of the block

Since the block in some cases tended to be short and since testing of the residual capacity of the hand requires a fairly long time (1—2 hours), not all of the 41 subjects were examined with all the tests described in chapter VIII Wartenberg s Sunderland s Egawa s and Froment s signs were however invariably demonstrated Practically all the subjects found it difficult to shape the hand to a cone A special sign the so called hyperflexion sign was also very often seen

Hyperflexion sign

In paralysis of the ulnar nerve the pinching grip is weak disintegrated and uncoordinated Bunnell (1956) and Boyes (1964) believe this weakness to be due mainly to loss of the function of the abductor of the index finger *i e* interosseus dorsalis I and to loss of the adductor of the thumb Boyes (1964) believes that on marked flexion the IP joint of the thumb tightens the extensor pollicis longus muscle which can thereby serve better as an adductor substitute

In the present series of ulnar nerve block the pinching grip was invariably found to be weakened Furthermore the grip was disintegrated in a very typical way the MP joint of the thumb is slightly hyperextended but not more than is allowed by the fibro cartilago volaris and that part *of the flexor pollicis brevis innervated by the median nerve (Masse s sign)* In the index finger the Mp joint is only slightly flexed and the PIP joint sets in hyperflexion *i e* more than 90 flexion The DIP joint is slightly hyperextended but not more than what is allowed by the fibro cartilago volaris The thumb and the index finger are in a supinated position and the index finger is occasionally deviated towards the ulnar side of the hand (Fig 29)

If the subject tries to strengthen the already weakened pinching grip the following sequence of events occur in the thumb and index finger

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If the subject tries to strengthen the already weakened pinching grip the following sequence of events occur in the thumb and index finger

Table 24 Disappearance of block

Investigation	N	$M_{minutes}$	s
1 Recovery of paresthesia	31	126	±43
2 Full sensibility	31	181	±47
3 *Wartenberg* sign neg	31	127	±42
4 Neg *hyperflex* sign *I—II I—III*	*24*	*118*	±57

ninhydrin method of Dhuner et al was on the average 156 min and after 133 min in Albert and Lofstrom s series In the present investigation the period of anesthesia lasted somewhat longer (181 ± 47 min see Table 24) In addition in the present investigation the figures were based on subjective evaluation by the subjects themselves *i e* when they thought that they had recovered sensibility

In Albert and Lofstrom s experiments after ulnar block with 1 % Carbocain® the duration of complete *muscle paralysis* was about 60 min In their series the motility was tested by examining the subjects capacity to flex the little finger with the Flexor digitorum profundus V Their technique differs therefore from that used in the present investigation (de*monstration of negative Wartenberg s sign) I thus studied the recovery* of motility of a distal intrinsic muscle *i e* third volar interosseus More over in the present investigation the ulnar nerve block lasted at last twice as long on the motor side and the series are therefore not comparable

The anesthesia in the present investigation also differs from that in the series of the aforementioned two groups of authors in that my subjects recieved a larger amount of 1 % Carbocain® without adrenalin intraneurally The dose used in the present investigation was 2—3 ml and in one case 3 5 ml intraneurally deposited The present subjects also received 3—4 ml extraneurally and one as much as 7 ml The total amount of anesthetic applied in the present 41 subjects was therefore on the average 6—7 ml (in *2 cases 8 ml)*

WHAT IS THE DISABILITY

The subjects were requested to note what they found difficult to perform at home as long as the ulnar block persisted

It should be remembered that on arrival home the block was decreasing It should also be recollected that none of the subjects were aware of the functions of the hand to be examined

The time of onset and disappearance of the sign of hyperflexion is given in Tables 23 and 24

Wartenberg's sign

This sign was positive in all 41 subjects examined In 34 in which the time of appearance of Wartenberg's sign was noted it was on the average 2 2± 1 6 min after induction of the block see Table 23 In 14 of the 34 cases the sign was positive within 1 minute.

Sunderland's sign

This sign appeared 2 3±2 min after induction of block in 33 subjects examined see Table 23

DISAPPEARANCE OF BLOCK

Table 24 refers to the examination performed by the subjects with ulnar nerve block, after they had come home They were requested to state the time of appearance of paresthesia and recovery of full sensibility This sensibility was tested in a cruder way namely by recovery of the sensation of touch But since a ninhydrin print was taken at this time the investigation nevertheless was acceptable. The subjects were also requested to note the recovery of the ability of the little finger to adduct towards the ring finger (negative Wartenberg's sign) and to state the time of recovery of a normal pinching grip between the thumb and index or long finger This means that the pathological hyperflexion sign had disappeared The values are given in Table 24

Discussion

Dhuner Edshage and Wilhelm (1960) and Albert and Löfstrom (1961) have tried anesthetics and recorded onset and duration of their effect. Both groups of authors used ulnar nerve block as an instrument Dhuner et al demonstrated loss of sensibility on the average 5 minutes after induction of ulnar nerve block in 15 cases Loss of sensibility was demonstrated by the ninhydrin method according to Moberg (1958) Albert and Lofstrom demonstrated loss of sensibility after ulnar block with Carbocain® in 25 female volunteers and 10 male medical students The loss of sensibility after ulnar nerve block with 1 % Carbocain® occurred on the average after 4 minutes While Dhuner *et al* used different anesthetics the spread in their series may have been somewhat greater than in Albert and Lofström's However the results obtained by both groups were in fairly good agreement with those found in the present investigation

The interval before full recovery of sensibility demonstrated with the

Table 25 Difficulties in high ulnar block

Difficulties	♂ N	♀ N	Σ
Put on glove	9	5	14
Write	8	4	12
Turn off taps	4	7	11
Turn key	4	6	10
Cut with knife	6	1	7
Do up buttons	3	2	5
Comb hair	1	4	5
Carry heavy bag	3	1	4
Type write	3	—	3
Strike a match	2	1	3
Fill a smoking pipe	3	—	3
Hold a tee-cup	1	2	3
Blow the nose	2	—	2
Wash	2	—	2
Hold and count coins	2	—	2
Do up shoe lace	2	—	2
Spread butter on bread	1	—	1
Shake hands	—	1	1

the ninhydrin test (Moberg 1958) and in some cases by electromyographic examination of the abductor pollicis brevis muscle together with measurement of the strength of that muscle

However electromyography with needle electrodes in the interosseus dorsalis I and in adductor pollicis showed activity at maximal voluntary contraction It should be stressed that the high ulnar block was complete according to the previously defined electromyographical criteria

Ulnar block was then induced proximally in zone III *i e* somewhat proximal to os pisiforme The activity in the interosseus dorsalis I and adductor pollicis then disappeared This was accepted as proof of a true Martin Gruber anastomosis The strength of the pinching grip of adduction of the thumb and radial abduction of the index finger was remarkably decreased and at the level of or in some cases somewhat lower than that measured after block in subjects with a normal innervation pattern in group I

Technical sources of error

The following sources of error were borne in mind throughout the examination

1 *Spread of stimulus from ulnar nerve to median nerve at level of high ulnar block*
2 Volume conduction from an approximate muscle innervated by the median nerve
3 Spread of anesthetic to the median nerve at the level of the wrist

These sources of error were also shown by Cassel (1964)

Results

The results are summarized in Table 26 page 141 which gives the normal values and those recorded after high and low ulnar block The possible extent and nature of the Martin Gruber anastomosis are recorded in Figs 30—36 pages 139—140

The cases are described below

Case ♂ 2

Though the high block was complete (Fig 37 38) the values noted for the strength of radial abduction of the index finger (Fig 39) and of the pinching grip were too high But the block had resulted in complete loss of sensibility of the little finger and in paralysis of flexor carpi ulnaris The strength of ulnar abduction of the little finger was also markedly reduced Martin Gruber anastomosis was suspected and low ulnar block was induced after which the values noted for the radial abduction of the index finger and of the pinching were much lower The ninhydrin printing test showed satisfactory sensibility in the region of the median nerve and electromyography of the musculature of abductor pollicis brevis showed that the motor branch of the median nerve had not been influenced by low ulnar block There was no unequivocal evidence that the Martin Gruber anastomosis supplied the adductor pollicis muscle Martin Gruber anastomosis probably supplies interosseus dorsalis I It cannot however be excluded that in this case the interosseus dorsalis I is also innervated to some extent by the median nerve (Fig 40) This case was not investigated further because high ulnar block had already been induced on 4 occasions in this subject

Summary

The investigation suggested the existence of a Martin Gruber anastomosis supplying interosseus dorsalis I

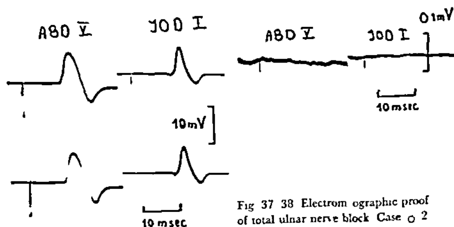


Fig 37 38 Electrom ographic proof of total ulnar nerve block Case o 2

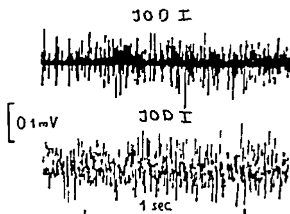


Fig 39 See text.

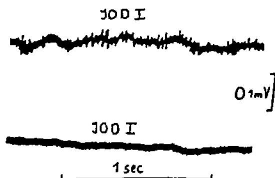


Fig 40 See text.

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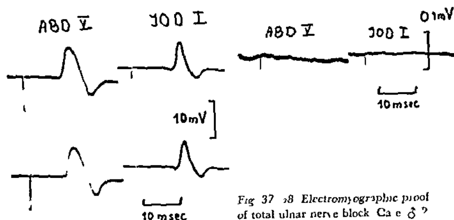


Fig 37–38 Electromyographic proof of total ulnar nerve block Case ♂ ?

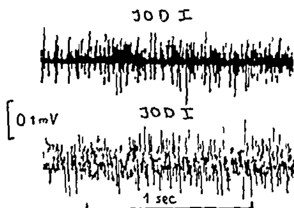


Fig 39 See text

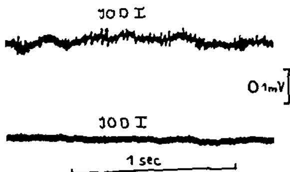


Fig 40 See text

Case ♂ 9

The high ulnar block was found to be complete This block resulted in total loss of sensibility of the little finger, paralysis of flexor carpi ulnaris musculature and very weak abduction of the little finger Compared with what was seen in the large group with a normal innervation pattern the pinching grip was found to be unusually strong as was radial abduction of the index finger and palmar adduction of the thumb On maximum voluntary contraction in the interosseus dorsalis I an electromyographic response was obtained from this muscle (see Fig 41) Martin Gruber anastomosis was suspected and low ulnar block was induced after which the electromyographic activity in the interosseus dorsalis I disappeared Fig 42 The low ulnar block had not spread to the median nerve Electromyographic examination with needle electrodes in the abductor pollicis brevis muscle showed normal activity Fig 43 The strength of radial abduction of the index finger decreased from 95 to 14 on the scale of the dynamometer, from 85 to 19 for the pinching grip and from 90 to 52 for the palmar adduction of the thumb When this palmar adduction was measured with the wrist flexed in the —50° position the value measured on the dynamometer was 2 This suggests that clinically the adductor pollicis musculature was paralysed and that the measuring value of 52 was due largely to the substituting strength exerted by the extensor pollicis longus (cf page 145)

Summary

A case of Martin Gruber anastomosis supplying interosseus dorsalis I and adductor pollicis is demonstrated

Case ♀ 14

High ulnar block was found to be complete and resulted in a total loss of sensibility of the little finger and paralysis of the flexor carpi ulnaris The strength of ulnar abduction of the little finger decreased from 95 to 22 on the scale of the dynamometer and Wartenberg s sign was positive But the residual strength in the interosseus dorsalis I and that of the pinching grip and of palmar adduction of the thumb were unusually high Martin Gruber anastomosis was suspected and low ulnar block was induced This resulted in complete paralysis of interosseus dorsalis I low values for the pinching grip and for palmar adduction When the hand was flexed —50 the subject could not adduct the thumb towards to 2nd ray This suggests that the value of 30 on the scale in this case was due to the extensor pollicis longus acting as a substituting muscle in adductor paralysis (cf page 145)



Fig 41 See text

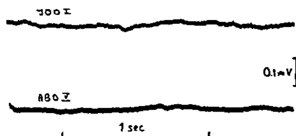


Fig 42 See text

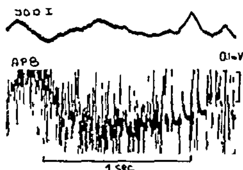


Fig 43 Martin Gruber anastomosis Case ♂ 9

Summary

The examination suggested Martin Gruber anastomosis supplying interosseus dorsalis I and adductor pollicis

Case ♂ 21

The high ulnar block proved to be complete The block resulted in complete loss of sensibility of the little finger and paralysis of the flexor carpi ulnaris muscle The strength of ulnar abduction of the little finger was markedly decreased and Wartenberg's sign was positive The strength of radial abduction of the index finger was also markedly reduced as was

Case O 9

The high ulnar block was found to be complete This block resulted in total loss of sensibility of the little finger paralysis of flexor carpi ulnaris musculature and very weak abduction of the little finger Compared with what was seen in the large group with a normal innervation pattern the pinching grip was found to be unusually strong as was radial abduction of the index finger and palmar adduction of the thumb On maximum voluntary contraction in the interosseus dorsalis I an electromyographic response was obtained from this muscle (see Fig 41) Martin Gruber anastomosis was suspected and low ulnar block was induced after which the electromyographic activity in the interosseus dorsalis I disappeared, Fig 42 The low ulnar block had not spread to the median nerve Electromyographic examination with needle electrodes in the abductor pollicis brevis muscle showed normal activity Fig 43 The strength of radial abduction of the index finger decreased from 95 to 14 on the scale of the dynamometer, from 85 to 19 for the pinching grip and from 90 to 52 for the palmar adduction of the thumb When this palmar adduction was measured with the wrist flexed in the —50° position the value measured on the dynamometer was 2 This suggests that clinically the adductor pollicis musculature was paralysed and that the measuring value of 52 was due largely to the substituting strength exerted by the extensor pollicis longus (cf page 145)

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Fig 45
Case ♂ 21 see text





Fig 46 Martin Gruber anastomosis Case ♂ 25 see text

Electromyographic examination of the interosseus dorsalis I and the abductor digiti quinti with needle electrodes showed residual activity on maximum voluntary contraction of these muscles (Fig 46) To check that the high ulnar block was still complete examination was repeated with high sensitivity and with needle electrodes in the interosseus dorsalis I and abductor digiti quinti A Martin Gruber anastomosis was suspected

Discussion

The nature of Martin Gruber's anastomosis has been elucidated by Ranschburg (1917), Borchart and Wjasmenski (1917) and others. They performed their investigations on cadavers. According to Ranschburg, Martin Gruber anastomosis supplies both the hypothenar musculature and most of the intrinsic muscles on the radial side of the hand.

Borchart and Wjasmenski, who used a refined technique, dissected some nerves in fasciculi and found Martin Gruber anastomosis to terminate in the deep motor ulnar branch.

SUMMARY

Of 41 subjects in whom high ulnar block was induced, a Martin Gruber anastomosis was suspected in 6, including 4 in whom the anastomosis was of true Martin Gruber type, 1 in whom it was probably and 1 in whom it was possibly of a Martin Gruber type. The nature of Martin Gruber anastomosis, *i.e.* the muscles finally innervated by this anastomosis, is discussed and the results are represented graphically. A preliminary report of these findings was given in 1964 by the author.

ANALYSIS OF ADDUCTION MOVEMENT OF THUMB IN ULNAR BLOCK

It has long been known that in ulnar paralysis the thumb can perform an adduction movement towards the 2nd ray (Fick 1845). There must thus be some muscles acting as substitutes to replace the loss of adductor pollicis and interosseus dorsalis I in ulnar paralysis. Remaining stabilisers in dorsal direction are the extensor pollicis longus and brevis, in volar direction flexor pollicis longus and that part of the flexor pollicis brevis innervated by the median nerve. In radial direction the thumb can still be stabilised by the extensor pollicis brevis and to some degree by the abductor pollicis *brevis and longus. In ulnar direction the thumb can no longer be stabilised* by the adductor pollicis or by the interosseus dorsalis I. Possible structures exerting a pull in ulnar direction here are the extensor pollicis longus and flexor pollicis longus.

The normal value found for 18 male students before ulnar block with the wrist at an angle of $\pm 0°$ was 141 ± 31 measured with the author's dynamometer. After ulnar block the gross strength of palmar adduction in these subjects was 27 ± 9. This strength must thus represent the gross strength of the substitute muscles (extensor pollicis longus and/or flexor pollicis longus).

Table 27 Muscles substituting the loss of adductor pollicis in total ulnar nerve lesion according to literature

Author	Extensor pollicis longus	Flexor pollicis longus
1 *Fick L* (1845)	+ (Extensor pollicis adducens	
2 *Duchenne* (1867)	+	—
3 *Babinski* and *Froment* (1918)	+	
4 *Foerster* (1929)	+	(+)
5 *Boyes* (1955)	+	
6 *Villiger Ludwig* (1946)		+
7 *Bodechtel et al* (1951)		+
8 *Wartenberg* (1953)		+
9 *Kaplan* (1965	+	
10 *Bunnell* (1956	—	
11 *v Lanz Wachsmuth* (1959)		+
12 *Bowden* and *Napier* (1961)		+
13 *McFarlane* (1962		+

+ = Adductor substitute
(+) = Weak adductor substitute
— = Denies adductor substitute

Is the extensor pollicis longus or flexor pollicis longus an adductor substitute in ulnar paralysis?

This question has received attention by various authors in this field (Table 27)

In an attempt to clear up this question 4 subjects with rupture of the extensor pollicis longus tendon and 2 subjects with lesions of the flexor pollicis longus tendon were studied (Table 28)

Comments on Table 28

The subjects with rupture of the extensor pollici longus tendon were examined before and after induction of ulnar block The following typical case is illustrative The patient a woman (A W had a subcutaneous rupture of extensor pollicis longus tendon on the right side after right sided fracture of the radius The patient was examined after the fracture had healed and was painless Under standardised conditions the palmar ad duction strength of the healthy (left) hand was measured and found to be 135 on the dial of the dynamometer After total ulnar block on the same

Table 28 Analysis of adductor substitute in ulnar nerve paralysis

	Pat.	Sex	Year	Strength of palmar adduction of the thumb			
				Injured hand		Healthy hand	
				Before	After block	Before	After block
Rupture EPL	AW	♀	53	75	0	135	34
	IL	♀	56	61	0	86	27
	RE	♀	53	70	0	70	*
	KA	♂	20	70	0	120	*
Lesion FPL	AN	♀	63	105	19	*	*
	TI	♂	43	160	25	*	*

* Not investigated

side the measurement was 34 Then the right hand with subcutaneous rupture of the extensor pollicis longus was examined Under equal standardised conditions the strength of palmar adduction was found to be 75 After complete ulnar block on this side the strength of palmar adduction was measured again Then the patient was unable to adduct the thumb from complete abduction against the pressure plate of the dynamometer, the value registered was 0 The flexor pollicis longus was undamaged This tendon could evidently not perform any substitute adduction movement against the metacarpale II A further 2 patients with rupture of extensor pollicis longus gave similar results after ulnar block In addition 1 case with laceration of the extensor pollicis longus was examined The results obtained were the same as in the other three

Two patients with lesions of the flexor pollicis longus were examined in the same way as the 4 patients with injured extensor pollicis longus tendon The gross strength of palmar adduction movement was before induction of ulnar block 105 and 160 respectively After high ulnar block the strength of palmar adduction fell to 19 and 25 respectively on the dynamometer

Summary

Four patients with rupture of extensor pollicis longus but with intact ulnar nerve function were examined regarding the strength of palmar adduction The strength varied between 61 and 75 After high ulnar block none of the

patients could adduct the first metacarpal towards the second In all these patients the function of the flexor pollicis longus tendon was intact.

Two patients with a lesion of flexor pollicis longus tendon but with an intact ulnar nerve function were examined regarding palmar adduction movement Both before and after induction of high ulnar block these 2 patients could adduct the first metacarpal towards the second In these 2 patients the function of the extensor pollicis longus was preserved

These examinations show the significance of the extensor pollicis longus in loss of function of adductor pollicis and interosseus dorsalis I and that it can adduct the first metacarpal towards the second The flexor pollicis longus has no effect on this movement These findings correspond with those I obtained in experiments on fresh autopsy specimens as described in Chapter IV

CHANGE IN THE STRENGTH OF PALMAR ADDUCTION IN HIGH ULNAR BLOCK WITH INCREASING VOLAR FLEXION OF THE WRIST

After induction of high ulnar block the strength of palmar adduction invariably decreased with increasing volar flexion (Fig 48) and when the wrist was in maximum volar flexion the first metacarpal could no longer be adducted to the second metacarpal bone What is the cause of this? The preceding investigations showed that the extensor pollicis longus is the adductor substitute in ulnar paralysis On increasing volar flexion of the wrist the position of the extensor pollicis longus tendon shifts to the radial side of the first metacarpal. On measurement of the strength of palmar adduction of a subject with increasing volar flexion of the wrist the extensor pollicis longus tendon could be made out by palpation This tendon was marked on the skin with barium contrast and under standard conditions the results of the examination were recorded with the help of roentgenography (see Fig 49) In this subject high ulnar block was induced and a certain amount of adduction of the thumb was possible with the aid of extensor pollicis longus Observe the gliding of the base of the first metacarpal in radial direction The extensor pollicis longus tendon here as normally—(see Fig 21)—was clearly on the ulnar side of the dorso volar axis in the adduction movement When the wrist was placed in maximum volar flexion the subject could no longer adduct the first metacarpal towards the second after induction of high ulnar block It is true that the extensor pollicis longus tendon was still intact but it lies over or on the radial side of the dorso-volar axis of movement Fig 50 shows the position of the extensor pollicis longus tendon after induction of ulnar block with the wrist in maximum volar flexion The tendon is situated

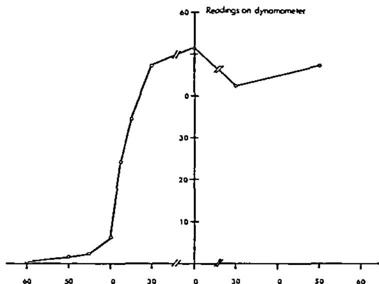


Fig 48 Case ○ 9 after induction of high ulnar block The strength of palmar adduction of the thumb decreases with increasing volar flexion in the wrist joint. With the wrist in maximum volar flexion (—60) the first metacarpal could no longer adduct towards the second Cause EPL tendon is on or radial to the axis of movement.

radially to the median plane of the first metacarpal This suggests that the extensor pollicis longus tendon lay radially to the axis of the movement of palmar adduction On normal palmar adduction the radial proximal part of the first metacarpal glides in radial direction therefore this dorso volar axis of movement should be distal to the carpo-metacarpal point I It did not prove possible to estimate the distance of the axis of movement from the carpo-metacarpal joint in distal direction The examination simply showed that the axis of movement of palmar adduction is situated distally to the carpo-metacarpal joint and ulnarly to the position of the tendon of the extensor pollicis longus in the last mentioned experiment where the subject was examined regarding palmar adduction with the wrist in maximum volar flexion after induction of high ulnar block

Some other experiments were also performed regarding the ability of the extensor pollicis longus tendon to adduct the first metacarpal towards the second After induction of high ulnar block the wrists of the subjects to be examined were placed in maximum volar flexion in the examination bridge As in the experiments just mentioned the subjects could not adduct the first metacarpal towards the second But when the examiner



Fig 49 Palmar adduction in high ulnar block. Case ♂ B.C The adduction is performed by EPL marked with barium contrast. The wrist joint is in slight dorsal extension



Fig 50 Same case as in Fig 49 Wrist joint in maximum volar flexion Palmar adduction not more possible. Cause EPL tendon on or radial to the axis of movement

pressed the extensor pollicis longus tendon in ulnar direction and so to say shifted this tendon on the ulnar side of the supposed dorso volar axis of movement of palmar adduction the subject could adduct the first meta carpal towards the second, (see Fig 51) This was recorded by films and by cineradiography About 3 ml Urographin 60 % was injected into the tendon sheath of the extensor pollicis longus in a person with ulnar pa ralysis At various angles of the wrist the patient was instructed to adduct the first metacarpal towards the second When the wrist was in maximum volar flexion the subject could not adduct the first metacarpal to the second unless the examiner first pressed the tendon of the extensor pollicis longus in ulnar direction and so to say past the position of the supposed dorso volar axis of movement

Another interesting observation was made on cineradiography after the tendon sheath of the extensor pollicis longus had been marked with Uro graphin 60 % When the wrist joint was in maximum volar flexion the patient could not adduct the first metacarpal towards the second The extensor pollicis longus tendon was thus situated radially to the supposed dorso volar axis of movement When the patient was then requested to perform palmar adduction at the same time as the hand was slowly ex tended dorsally in the wrist joint the extensor pollicis longus tendon in a certain position suddenly glided over in ulnar direction, after which the patient could adduct the first metacarpal towards the second The experi ment was repeated several times and the extensor pollicis longus tendon always slipped over in ulnar direction at the same angle of the wrist

SUMMARY

After induction of high ulnar block the strength of palmar adduction decreases with increasing volar flexion of the wrist This appears to be due to the fact that the only substituting muscle namely the extensor pollicis longus with its tendon slips more and more in radial direction with increasing volar flexion of the wrist At maximum volar flexion of the wrist the tendon glides so far in radial direction that it slides radially to the dorso volar axis of movement of the palmar adduction Thus the dorso volar axis of movement of the palmar adduction of the thumb lies distally to the first carpo metacarpal joint and ulnarly to the position of the ex tensor pollicis longus tendon on maximum flexion of the wrist It was not possible to determine the site of the axis more precisely

IS INTRANEURAL ULNAR BLOCK HAZARDOUS?

All values recorded on day 13 *i e* 6 days after induction of ulnar block were the same as those recorded on day 1 *i e* 6 days before the induction

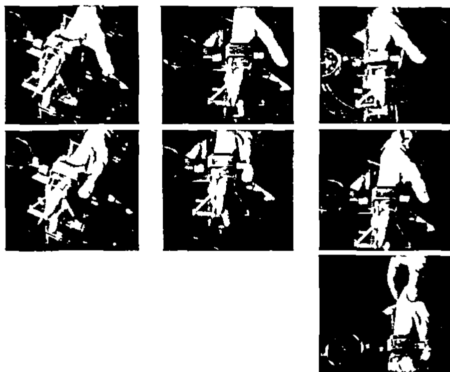


Fig 51 Palmar adduction in high ulnar block Case ♂ 21 Palmar adduction possible with the aid of EPL In volar flexion of the wrist joint the subject could not adduct the thumb against the index finger unless the examiner displaced the EPL tendon to the ulnar side of the axis of movement.

of the block except for some of the tests on some of the female students on day 13 which were lower than on day 1 At re-examination half a year later on these females the values noted were the sames as or higher than those originally recorded on day 1

When questioned all 41 subjects taking part in the investigation denied any sequelae after the block Only 1 subject (♂ 3) had temporary pain for a period of 2 weeks and therefore electromyography was performed and nerve conduction velocity was determined some time after the intraneural block The electromyographic pattern and the nerve conduction velocity at the re examination were normal

It would therefore appear safe to study paralysis in the region of the hand by the method used in the present investigation *i e* intraneural block of the ulnar nerve at the level just above the sulcus nervi ulnaris with 1 % Carbocain® without adrenalin Clinical experience supports this conclusion since only rarely do patients complain of subsequent pain at

the site of the injection Such pain may be related to ischaemia of the nerve because of too large an amount of adrenalin in the local anesthetic or of the tip of the needle becoming hooked by contact with bone and consequent injury to a nerve fasciculus on withdrawal of the needle after the injection No such hooking was noted in the present material

SUMMARY CHAPTER X

The main purpose of the investigation was to evaluate the residual capacity of the hand in a state of ulnar nerve paralysis 41 persons including the author subjected to a high ulnar nerve block were examined under the same standardised conditions as the controls (Chapters VI+VII) The ulnar blocks were classified as total according to the technique described in Chapter IX The residual capacity was determined both with the authors dynamometer and with Collin s dynamometer Moreover, two other tests were used, Mobergs picking up test (Moberg 1958) with registration of the time required and a so-called pin test (piercing through a paper with a needle) Finally the pattern of loss of sensibility was determined Statistical treatment of the values obtained in the group with normal pattern of innervation is given in tabular form at the end of the book The results are discussed under General discussion and conclusions The results after analysis of the palmar adduction in ulnar paralysis are also discussed under these headings

The question whether ulnar block is hazardous is discussed The values recorded 6 days after the ulnar block were not lower than those obtained before the block and none of the subjects complained of any pain at the site of injection with the exception of one subject who complained of some pain in the arm and hand 2 weeks after induction of a high ulnar nerve block and a low median nerve block Electromyographic investigation including estimation of nerve conduction velocity was therefore performed some time after the nerve blocks and at that re examination everything was normal Intraneural ulnar block performed with 1 % Carbocain® without adrenalin at the level just above the sulcus nervi ulnaris therefore appears to be safe and can thus be used in the study of ulnar nerve paralysis

When analysing the results it soon became obvious during the investigation that in certain subjects—6 of 41—the injection did not produce ulnar paralysis but only a certain degree of ulnar palsy (paresis) A Martin Gruber anastomosis was suspected and these 6 subjects were then given an intraneural injection in the ulnar nerve proximal to zone III with the same local anesthetic Ulnar paralysis now occurred in 4 of these subjects and a Martin Gruber anastomosis was thereby evident In the other 2 a Martin Gruber anastomosis could not be excluded by this technique

Part VII Clinical series

Chapter XI Clinical series

From 1962—1964 some 50 nerve injuries of the upper limb were examined and treated at the Department of Orthopaedic Surgery, University Hospital, Lund. Not few of the patients had total or partial ulnar nerve lesions. Some of the total ulnar lesions were not studied primarily with the author's technique. This was because the primary injury was so extensive that loss of ulnar function could not be fully measured. Other ulnar nerve lesions were associated with tendon lesions and/or fractures. Some of them were associated with median nerve injury. Some of the injuries occurred in children who were difficult to examine. This left 11 patients (Table 29). All of them had total lesion of the ulnar nerve with the exception of the patients in cases 2 and 11 who had total lesion of only the motor branch of the ulnar nerve. The material consisted of 10 men and 1 woman aged 7—68 years. The injuries involved zone I to zone III. In none of them was zone IV injured. In case 3 (K.E.N. ♂ 48 years) there may have been a Martin Gruber anastomosis. After induction of low ulnar block distally in zone III the value for the pinching grip dropped from 105 to 40 degrees.

Table 29 and Fig. 52 show some agreement between the values measured in the 11 patients with total motor injury of the ulnar nerve compared with the block values noted in the volunteers. In this comparison, however, it should be borne in mind that the clinical material with ulnar injury is heterogeneous and that the figures are only rough means. Nor were the measurements always made under standardised conditions. Even if these factors be considered, it would appear justified to give the arithmetic means for 11 patients with injury of the motor branch of the ulnar nerve alongside of the normal and blocked values, see Fig. 52.

SUMMARY

In 11 patients with total ulnar nerve injury in various zones the average values found for strength of the pinching grip, palmar adduction of the thumb, radial abduction of the index finger and ulnar abduction of the little finger tended to resemble those found in subjects with induced ulnar

Table 29 Clinical cases with ulnar nerve paralysis

No	Pat.	Age	Sex	Zone	PINCH	ADD POLL	ABD II	ABD V
1	VS	68	♂	III	45	20	—	—
2	AH	60	♂	III	42	20	0	0
3	KEN	48	♂	I	105/40	25	40	0
4	GG	45	♂	I	43	31	15	10
5	AP	32	♂	III	46	14	0	—
6	KA	18	♂	III	28	48	30	18
7	HA	15	♂	I	35	30	20	—
8	AP	14	♀	II	45	45	5	12
9	SC	11	♂	II	45	10	12	0
10	KJ	10	♂	III	15	40	10	16
11	SC	7	♂	III	45	19	10	2
Highest		68		I	46	48	40	18
Lowest		7		III	15	10	0	0

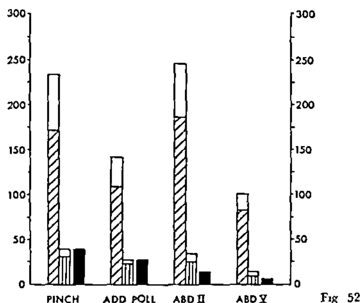


Fig 52

Arithmetic mean of median values of 3 measurements in each subject in each test under normal conditions

Arithmetic mean of median values of 3 measurements in each subject in each test in high ulnar block

Arithmetic mean of entire clinical series

block The clinical series was small inhomogeneous and not always measured under standardised conditions It was nevertheless considered justified to include it in the present investigation for comparison

General discussion and conclusions

The hand is supplied by three main nerves the radial the median and the *ulnar nerve*

During the first world war the most commonly damaged nerve in the upper limb was the radial nerve (Pollock 1919 Foerster 1929) but during the second world war and also in modern civil practise it was the ulnar nerve — af Bjorkesten (1947) Woodhall (1947) Zachary (1954) Zachary and Roaf (1954) Nicholson and Seddon (1957) Bateman (1962) Mumenthaler and Schliack (1965) This difference can be explained by advances made in our knowledge of the anatomy and function of the hand In other words the diagnosis of lesions of the median and ulnar nerves has improved

No systematic study of the residual capacity of the hand in ulnar nerve paralysis seems to be available The reason for this is at least twofold the lack of an adequate method for estimation of loss of strength of muscles governed by the nerve and a lack of a uniform series with ulnar nerve paralysis

Mumenthaler (1961) in his monograph on ulnar nerve palsy refers to more than 350 papers concerning ulnar nerve lesions but the published series are either too small or too inhomogenous to serve as a reliable basis for judging the residual capacity of the hand in ulnar nerve paralysis

To overcome these disadvantages in the present investigation a dynamometer was designed and measurements were made under standardised conditions in a control group of 100 healthy persons studied twice once on day 1 and again on day 13 *The isometric strength of the following* grips and movements was determined pinching grip palmar adduction of the thumb radial abduction of the index finger adduction in the second and fourth interspaces and ulnar abduction of the little finger The values obtained were used as references in the evaluation of the residual capacity of some functions of the hand in ulnar nerve paralysis in a group of 40 volunteers investigated 3 times *i.e.* on days 1 7 and 13 On day 7 intraneural block of the ulnar nerve was induced at the level of the elbow with a local anesthetic 1 % Carbocain® without adrenalin A special technique was devised to check that the ulnar nerve block was complete When

supramaximal stimuli proximal to the nerve block did not produce action potentials in the abductor digiti quinti muscle or in the musculature of the first dorsal interosseus the nerve block was said to be complete Never theless some objections against this technique could be raised Therefore a more refined pilot test was performed which showed that the technique used was satisfactory

With the measuring technique used the residual capacity proved to be much lower than that formerly believed Thus af Bjorkesten (1947) and Bunnell (1956) estimated the residual capacity of a hand in ulnar nerve paralysis as half or a third of normal The figures in the present in vestigation showed that the residual capacity of the pinching grip and of palmar adduction of the thumb was 17—20 % of normal Although these measurements were made during acute ulnar nerve paralysis they in dicate a higher sensitivity of the measuring technique used The error of method was small and acceptable

In 6 of the 40 persons repeated injections failed to induce ulnar nerve paralysis A Martin Gruber anastomosis was suspected and all 6 subjects were given an additional ulnar nerve block in the region of the wrist Four of the subjects proved to have a true Martin Gruber anastomosis In the fifth such an anastomosis was probable and in the sixth it could not be excluded This Martin-Gruber anastomosis which was first described in 1763 by the Swedish anatomist Martin passes between the median and the ulnar nerve in the forearm Despite serious later attention (Gruber 1870 Borchart and Wjasmenski 1917 and Ranschburg 1917) the nature of the anastomosis i e which end organs it finally supplies remained ob scure With the technique used in the present investigation the anastomosis was sometimes seen to supply the first dorsal interosseus and/or the ad ductor pollicis muscles Moreover in one or two cases it could not be ex cluded that the anastomosis supplied also the musculature of the abductor digiti quinti These findings have also been published in a preliminary report (Mannerfelt 1964) Goldner and Jones (1966) reported some in stances of the anastomosis but otherwise the clinical literature on this important communication between the median and ulnar nerves in the forearm is meagre The occasional rapid regeneration after suturing of an ulnar nerve severed at the level of the elbow can doubtless be explained by the presence of this anastomosis The technique described for de monstrating the presence of such an anastomosis is simple and reliable

There is also another sort of anomalous innervation of importance ii the so called Riche Cannieu anastomosis running between the motor branch of the median nerve and the deep branch of the ulnar nerve in the radial part of the hand It has been described by several authors (Turner 1874 Riche 1897 Cannieu 1897 Ranschburg 1917 Gehwolf 1921 Foerster

1929) but it is still an open question whether it is of sensory motor or mixed function Nor is it known whether the anastomosis is a constant phenomenon Finally it is of interest to know whether the nerve passes from the ulnar to the median nerve or in the opposite direction Judging from the literature these problems are still unsolved. In the present series of 40 ulnar nerve blocks possibly one subject might have had such an ana stomosis To form a personal opinion of this anastomosis 9 hands were dissected and studied with special reference to the ulnar nerve A Riche Cannieu anastomosis was found in 3 of them. The conjugation undoubtedly connected the deep motor ulnar branch with the motor branch of the median nerve. In a fourth pecimen there was a double innervation of the adductor pollicis muscle it received nerve fibres from the ulnar as well as from the median nerve. This supports Foerster s (1929) opinion that the anastomosis is of motor type The number of specimens dissected was not large enough to allow any conclusions on the frequency of the Riche Cannieu anastomosis. Nor could it be decided whether the ana stomosis passes from the ulnar to the median nerve or in the opposite direction Many of the problems bearing on the Riche Cannieu anastomosis must therefore abide further research

It is known (Bunnell 1956) that certain grips are stronger when the wrist is in slight dorsal extension — position of function" Measurements of the strength of the *pinching grip palmar adduction of the thumb* and *radial abduction of the index finger* were therefore made with the wrist joint in different degrees of volar flexion and dorsal extension With the exception of the hyperextended position the strength of the pinching grip did not vary with the angle of the wrist. This was so both in the control series and in the group with ulnar nerve block. The strength of the pinching grip can therefore be measured regardless of the angulation of the wrist joint within the limits of 30° volar flexion and 50 dorsal extension.

Concerning the strength of *palmar adduction of the thumb* in ulnar nerve paralysis it decreased as volar flexion approached its maximum This was because of the radial shift of the extensor pollicis longus tendon on increasing volar flexion of the wrist joint. This phenomenon is analysed below in connection with the discussion of substituent muscles in ulnar paralysis and palmar adduction of the thumb

The values found for *radial abduction of the index finger in ulnar nerve paralysis* tended to decrease with increasing volar flexion of the wrist joint. This might have been due to a reduction of the strength of the long ex tensors in this position of the wrist joint.

The values found for the pinching grip and palmar adduction of the thumb thus lend no support to the widely accepted view that the hand

is strongest when the wrist is in slight dorsal extension It should however be borne in mind that this refers to grasping of larger objects with long flexors of the hand Therefore the values obtained in the present investigation cannot be used to illustrate the question under discussion

The *strength of adduction in the second interspace* varies with the flexion of the MP joints. In the flexed position (=120°) the strength is greater both in normal conditions and in high ulnar nerve block This is partly because of the decreased strength of the long extensors and partly because of additional adduction by the long flexors

In ulnar nerve paralysis the *strength of adduction in the fourth interspace* is nil This is because of paralysis of the 3rd volar interosseus Long flexors of the little finger can obviously not substitute any adducting force The pull in ulnar direction by the long extensors when the MP joint is in extended position also deserves mentioning

Ulnar abduction of the little finger is stronger when MP joint V is extended than when it is flexed (=120) for then it is nil This can presumably be explained by a weakening of the long extensors when the MP joint V is flexed and by tightening of the collateral ligaments This applies to normals and to subjects with ulnar nerve paralysis where also the short abductor and the short flexor are functionless

The investigation included a picking up test (Moberg 1958) and the time required by the subjects to perform the test was recorded The results clearly showed that a person with ulnar nerve paralysis has great difficulties to perform precision movements in the dark or when he must do something with his hand without being able to see what he is doing *e g* screwing nuts and bolts in positions hidden from view The picking up test is not used consequently before on time and during standardised conditions The values obtained in the author s control series could therefore be used as a sort of normal values for male and female persons between 18 and 30 years under the conditions used

Perusal of the literature failed to reveal any analysis of palmar adduction movement of the thumb *i e* the position of the axis of movement extrinsic muscles that can substitute the adduction of the thumb in ulnar nerve paralysis and variation if any in the strength of the palmar adduction of the thumb with increasing volar flexion of the wrist joint in ulnar nerve paralysis For this purpose 14 specimens fresh enough to allow adduction movements were dissected The CMC joint I was also dissected with special reference to the ligament apparatus Analysis of these preparations and of roentgenograms and electromyograms of volunteers and of patients with ulnar nerve paralysis revealed that on palmar adduction of the thumb the base of the first metacarpal glided in radial direction in the CMC joint I both in normal conditions and in ulnar nerve

paralysis The axis of movement thus lies *not in* the joint but *distal* to it Studies with ulnar nerve block in patients with rupture of the extensor pollicis longus tendon and on others with lesions of the flexor pollicis longus tendon clearly revealed that the extensor pollicis longus and not the flexor pollicis longus is the adductor substituent of the thumb in ulnar nerve paralysis and thereby confirmed the opinion of Fick (1845) Duchenne (1867), Babinski and Froment (1918) Boyes (1935) Kaplan (1965) and Bunnell (1956) and disproved the view of inter alia Villiger Ludwig (1946) Wartenberg (1953) v Lanz Wachsmuth (1959), Bowden and Napier (1961) and Mc Farlane (1962) that the flexor pollicis longus is the adductor substitute in ulnar nerve paralysis Finally it was found that strength of the adduction exerted by the extensor pollicis longus in ulnar nerve paralysis decreases to practically nil as volar flexion of the wrist joint approaches maximum This is because in maximum volar flexion the tendon of extensor pollicis longus shifts radially on or past the axis of movement This was also shown by cineradiography after injection of barium contrast into the tendon sheath of the extensor pollicis longus in a patient with ulnar nerve paralysis

The onset and disappearance of the ulnar nerve block was studied on the motor side and on the sensory side Thus Wartenberg s sign and Sunderland s sign (motor paralysis) occurred earlier than loss of sensibility in the distal volar part of the little finger Motor function returned sooner than full sensibility

Concerning the area of sensory loss after high ulnar block, the findings in the present investigation were not entirely in accord with common anatomical textbooks This was the case regarding the dorsal and ulnar part of the long finger where none of 32 blocked and specially investigated subjects had sensory loss In anatomical text books e g Villiger and Ludwig (1946) and v Lanz Wachsmuth (1959) sensory loss in ulnar nerve paralysis also involves the dorsal and ulnar part of the long finger

An important question is whether intraneural blocks with 1 % Carbocain® without adrenalin is followed by any sequelae A nerve block is useful in the investigation of ulnar nerve paralysis and has been used to evaluate local anesthetics (Dhuner Edshage and Wilhelm 1960 Albert and Lofstrom 1961) In the present investigation all 41 volunteers subjected to intraneural blocks were re examined 6 days after injection of the local anesthetic Only one complained of pain at the site of injection some weeks after the nerve block but at re examination some weeks later both the conduction velocity of the ulnar nerve and electromyographic studies of muscles governed by the nerve appeared to be normal besides which the pain had disappeared In all 41 subjects except in some females the strength of the muscles studied was the same before as 6 days after the intra

neural block These few females were re examined 6 months later and then the strength of the muscles was the same as before the block It may therefore be concluded that intraneural block with a fine needle in the ulnar nerve at a level just above the sulcus nervi ulnaris with a reasonable amount of 1 % Carbocain® without adrenalin will cause no sequelae

Eleven patients with post traumatic ulnar nerve paralysis were investigated The examination included measurements with the dynamometer but not always under standardised conditions Although the ages of these patients varied widely as well as the level of the lesions the values obtained were fairly similar to those recorded in the ulnar nerve block group This means that artificially induced ulnar nerve paralysis by intraneural injection of a suitable local anesthetic in volunteers can be used with advantage in the elucidation of clinical ulnar nerve paralysis

Summary

1. The ulnar nerve is the most frequently injured nerve in the upper extremity.
2. A special dynamometer was constructed to measure the strength of certain grips and muscles governed by the ulnar nerve.
3. Normal values were calculated from measurements made with the dynamometer in a control group consisting of 100 healthy volunteers under standardised conditions.
4. These values were used as reference in the evaluation of the residual capacity of some functions of the hand in ulnar nerve paralysis. The paralysis was induced with a local anestetic (1 % Carbocain® without adrenalin) injected intraneurally into the nerve in 40 volunteers.
5. A special electromyographic technique never used before for this purpose was applied to check that the ulnar block was complete.
6. The residual strength of the pinching grip and of palmar adduction of the thumb was 17—20 % of the normal, which is lower than what is widely believed.
7. In 6 of the 40 subjects a Martin Gruber anastomosis in the forearm was demonstrated or suspected. The possible existence of this anastomosis must be borne in mind in the investigation of periferal nerve injuries in the arm or hand.
8. Measurement of the pinching grip with the dynamometer can be performed with the wrist between 30° of flexion and 50° of extension without influencing the accuracy of the method both in normal conditions and in ulnar nerve paralysis.
9. In ulnar nerve paralysis palmar adduction of the thumb is low or nil when the wrist joint is in maximum volar flexion. This is due to the radial shift of the extensor pollicis longus tendon towards the radial side during volar flexion of the wrist joint.
10. In ulnar nerve paralysis the substitutent muscle in the adduction movement of the thumb is the extensor pollicis longus muscle and not the flexor pollicis longus muscle.
11. The axis of movement in the palmar adduction of the thumb lies not in the carpometacarpal joint I but distally to it.

12 A picking up test according to Moberg (1958) was used and timed to determine the residual capacity of some grip functions of the hand in ulnar nerve paralysis. The results showed that the working capacity of the hand when hidden from view is severely impaired in ulnar nerve paralysis.

13 Intraneural block with a reasonable amount of 1 % Carbocain® without adrenalin at the level of the elbow is not followed by any sequelae.

14 The residual capacity of some hand functions in patients with post-traumatic ulnar nerve paralysis was about the same as in experimentally induced ulnar nerve paralysis in healthy volunteers.

Summary

1. The ulnar nerve is the most frequently injured nerve in the upper extremity.
2. A special dynamometer was constructed to measure the strength of certain grips and muscles governed by the ulnar nerve.
3. Normal values were calculated from measurements made with the dynamometer in a control group consisting of 100 healthy volunteers under standardised conditions.
4. These values were used as reference in the evaluation of the residual capacity of some functions of the hand in ulnar nerve paralysis. The paralysis was induced with a local anestetic (1 % Carbocain® without adrenalin) injected intraneurally into the nerve in 40 volunteers.
5. A special electromyographic technique, never used before for this purpose, was applied to check that the ulnar block was complete.
6. The residual strength of the pinching grip and of palmar adduction of the thumb was 17—20 % of the normal, which is lower than what is widely believed.
7. In 6 of the 40 subjects a Martin Gruber anastomosis in the forearm was demonstrated or suspected. The possible existence of this anastomosis must be borne in mind in the investigation of periferal nerve injuries in the arm or hand.
8. Measurement of the pinching grip with the dynamometer can be performed with the wrist between 30° of flexion and 50° of extension without influencing the accuracy of the method both in normal conditions and in ulnar nerve paralysis.
9. In ulnar nerve paralysis palmar adduction of the thumb is low or nil when the wrist joint is in maximum volar flexion. This is due to the radial shift of the extensor pollicis longus tendon towards the radial side during volar flexion of the wrist joint.
10. In ulnar nerve paralysis the substitutent muscle in the adduction movement of the thumb is the extensor pollicis longus muscle and not the flexor pollicis longus muscle.
11. The axis of movement in the palmar adduction of the thumb lies not in the carpometacarpal joint I but distally to it.

12. A picking-up test according to Moberg (1958) was used [illegible] to determine the residual capacity of some grip functions [illegible] hand in ulnar nerve paralysis. The results showed that [illegible] capacity of the hand when hidden from view is severely impaired [illegible] ulnar nerve paralysis.

13 Intraneural block with a reasonable amount of 1 % Carbocaine [illegible] out adrenalin at the level of the elbow is not followed [illegible] quelae.

14 The residual capacity of some hand functions in patients with traumatic ulnar nerve paralysis was about the same as in experimentally induced ulnar nerve paralysis in healthy volunteers.

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Tables

Table 30 Mean values pinching grip group ♂ I—V

Position of wrist joint		+70			+50			+30			±0			—30		
Sex	Day	N	M	s	N	M	s	N	M	s	N	M	s	N	M	s
♂	1	5	156	46	5	181	49	5	195	35	5	203	47	5	210	41
	7 A	5	164	30	5	208	20	5	214	24	5	229	49	5	221	34
	7 B	5	37	6	5	30	8	5	34	6	5	35	5	5	35	10
	13	5	161	28	5	230	39	5	257	28	5	254	26	5	263	38

Table 31 Mean values palmar adduction of thumb group ♂ I—V

Position of wrist joint		+50			+30			±0			—30			—50		
Sex	Day	N	M	s	N	M	s	N	M	s	N	M	s	N	M	s
♂	1	5	118	27	5	129	22	5	130	33	5	131	42	5	126	37
	7 A	5	127	23	5	136	47	5	144	45	5	152	51	5	144	43
	7 B	5	36	9	5	30	9	5	36	5	5	27	13	5	23	18
	13	5	131	28	5	144	32	5	150	35	5	147	33	5	141	38

Table 32 Mean values radial abduction of index finger group ♂ I—V

Position of wrist joint		+30			±0			—30		
Sex	Day	N	M	s	N	M	s	N	M	s
♂	1	5	176	27	5	192	33	5	167	33
	7 A	5	214	24	5	215	28	5	196	22
	7 B	5	51	21	5	44	14	5	32	8
	13	5	210	31	5	222	32	5	204	27

Table 33 Mean values adduction in second interspace group ♂ I—V

Position of MI joint		180			120		
Sex	Day	N	M	s	N	M	s
♂	1	[illegible]	[illegible]	[illegible]	5	121	30
	[illegible]	[illegible]	[illegible]	[illegible]	5	148	29
	7 B	[illegible]	[illegible]	[illegible]	5	31	10
	13	5	[illegible]	[illegible]	5	[illegible]	[illegible]

Table 34 Mean values adduction in fourth interspace group ♂ I—V

Position of MI joint		180			120		
Sex	Day	N	M	s	N	M	s
♂	1	5	80	28	5	104	29
	7 A	5	64	14	5	105	12
	7 B	5	*0*	*0*	5	*0*	*0*
	13	5	58	18	5	103	7

Table 35 Mean values ulnar abduction of little finger group ♂ I—V

MI joint		180			120		
Sex	Day	N	M	s	N	M	s
♂	1	5	93	17	5	84	13
	7 A	5	94	23	5	84	11
	7 B	5	*16*	*9*	5	*0*	*0*
	13	5	100	16	5	97	14

Table 36 Mean values pinching grip
groups ♂ 1—25 and ♀ 1—10

Position of wrist joint		+70			+50			+30			±0			—30		
Sex	Day	N	M	s	N	M	s	N	M	s	N	M	s	N	M	s
♂	1	15	162	33	15	230	56	17	233	57	15	241	53	15	225	49
	7 A	15	156	35	15	231	42	17	235	45	15	220	50	15	211	46
	7 B	15	31	12	15	34	11	17	39	12	15	39	15	15	37	13
	13	15	150	29	15	228	39	17	242	46	15	233	47	15	225	50
♀	1	9	123	39	9	164	39	9	171	36	9	171	35	9	163	30
	7 A	9	109	33	9	159	26	9	175	28	9	166	27	9	161	40
	7 B	9	29	11	9	30	9	9	30	11	9	29	7	9	30	8
	13	9	97	33	9	148	26	9	172	37	9	157	26	9	146	27

Table 37 Mean values palmar adduction of thumb
groups ♂ 1—25 and ♀ 1—10

Position of wrist joint		+50			+30			±0			—30			—50		
Sex	Day	N	M	s	N	M	s	N	M	s	N	M	s	N	M	s
♂	1	16	121	31	16	135	31	18	141	31	16	139	37	16	125	35
	7 A	16	123	32	16	142	44	18	152	39	16	147	42	16	133	36
	7 B	16	30	13	16	26	6	18	27	9	16	22	11	16	17	11
	13	16	120	31	16	130	33	18	144	34	16	137	38	16	129	35
♀	1	9	98	26	9	107	29	9	109	26	9	110	27	9	102	27
	7 A	9	102	20	9	113	25	9	113	27	9	116	30	9	109	26
	7 B	9	28	13	9	26	11	9	25	12	9	26	11	9	23	11
	13	9	94	24	9	107	25	9	114	21	9	107	26	9	96	19

Table 38 Mean values radial abduction of index finger groups ♂ 1—25 and ♀ 1—10

Position of wrist joint		+30			±0			−50		
Sex	Day	N	M	s	N	M	s	N	M	s
♂	1	16	252	34	18	245	40	16	13	38
	7 A	16	234	23	18	8	33	16	211	27
	7 B	16	34	0	18	4	17	16	25	15
	13	16	242	34	18	[illegible]	35	16	25	28
♀	1	9	187	35	9	186	53	9	163	23
	7 A	9	189	31	9	196	35	[illegible]	181	34
	7 B	9	28	8	9	25	9		23	11
	13	9	177	42	9	190	40	9	181	41

Table 39 Mean values adduction in second interspace groups ♂ 1—25 and ♀ 1—10

Position of MP joint		180			120		
Sex	Day	N	M	s	N	M	s
♂	1	15	94	19	15	138	28
	7 A	15	104	24	15	144	35
	7 B	15	28	12	15	43	13
	13	15	109	15	15	150	32
♀	1	9	91	13	9	116	19
	7 A	9	92	10	9	121	17
	7 B	9	22	9	9	33	17
	13	9	85	17	9	112	21

Table 40 Mean value adduction in fourth interspace groups ♂ 1—?ɔ and ♀ 1—10

Position of MP joint		180			120		
Sex	Day	N	M	s	N	M	s
	1	16	66	22	16	9/	23
	7 A	16	61	13	16	93	1ɔ
	/B	16	0	0	16	0	0
	13	16	6/	17	16	97	14
♀	1	9	5?	2?	9	78	?1
	7 A	9	ɔ6	13	9	/8	16
	7 B	9	0	0	9	0	0
	13	9	49	18	9	81	13

Table 41 Mean values ulnar abduction of little finger groups ‿ 1—2ɔ and ♀ 1—10

Position of MP joint		180			120		
Sex	Day	N	M		N	M	s
○	1	16	101	19	16	83	19
	7 A	16	99	?1	16	8ɔ	18
	7 B	16	14	10	16	0	0
	13	16	10?	1/	16	93	17
♀	1	9	83	9	9	73	11
	7 A	9	82	13	9	/0	16
	7 B	9	9	6	9	0	0
	13	9	80	12	9	71	‿8

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FORCES ACTING ON THE FEMORAL HEAD-PROSTHESIS

A Study on Strain Gauge Supplied Prostheses in Living Persons

by
NILS W RYDELL

Munksgaard, Copenhagen 1966

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I often say that when you can measure what you are speaking about and express it in numbers you know something about it but when you cannot measure it when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind

(*Lord Kelvin* Popular lectures and addresses. Vol 1 p 80 Macmillan 1891)

Introduction

Numerous attempts have been made to determine the magnitude and direction of the forces acting on the hip joint. The theories that shape and internal structure of the femoral head and neck are related to stress and strain the mechanism of femoral neck fractures and the frequently occurring failure of its internal fixation have led to analyses of the forces involved It is believed that pathological conditions of the hip are influenced by mechanical factors and many reconstructive procedures in this region are based on mechanical considerations

At present all our knowledge of the forces acting on the hip-joint comes from theoretical calculations and tests on specimens and models Most of the results are based on 2 dimensional studies

The use of theoretical calculations has its limitations and direct measurements by means of strain gauges in the hip under living conditions is another way to get information about forces acting on the hip joint Recordings from strain gauges applied to living bone are at present not reliable due to the physical properties of bone Therefore metal prostheses substituting the upper femur, with built in strain gauges were designed and manufactured. These prostheses permit measurements of forces present to be determined as to its magnitude and direction

The results obtained with these prosthesis are only valid for the prosthetic hip but they could provide information applicable to normal hips if factors such as lever arms and directions of muscular pull are known about the normal and prosthetic hip Recordings can be made from a patient with such a measuring prosthesis under different activities involving the hip such as standing walking running etc.

For the analyses while walking a device describing the forces between the foot and the ground in consecutive steps was desirable Therefore two electronic walk ways were constructed one for the left foot and one for the right

This work has been divided in 5 parts In the first part, historical reviews of studies on the shape and internal structure of the proximal femur, force analyses and the development of force plates are presented The second and third parts discuss the construction of the measuring prosthesis and the electronic walk-ways The intravital measurements and the results are reported in the fourth part and in the fifth part the investigation is recapitulated discussed

I Survey of the literature

Structure of the proximal femur

In his work on strength of material Galilei (1638) discussed the loadbearing capacity of bones Later many others dealt with the same subject among them Ward (1838), Wyman (1850) Haughton (1864), Meyer (1867) Wolf (1870—1900) Roux (1893—1896) and Pauwels (1948—1958) They are of the opinion that there is a connection between design and function of the bone

The design of the proximal femur the head and the neck and its internal architecture has been the subject for mechanical analyses

The hip joint is a ball and socket joint The head of the femur is not a perfect sphere It is slightly compressed in an approximately ventro dorsal direction The difference between the two principal axes is very small the ratio between them being 1 02

The femoral neck lies in a distal lateral direction from the head It is a 30—40 mm long tube and like the head, is compressed in an approximate ventro dorsal direction The neck changes its shape in its course At its junction with the head a section through the neck is almost cylindrical The shape of neck increasingly becomes elliptical in a distal-lateral direction In the middle of the neck, the ratio between the two principal axes is 1 15 and at the junction between the neck and the femoral shaft the ratio is 1 65 (Backman 1957)

The direction of the major axis of the elliptical section does not have the same direction as the long axis of the femoral shaft The major axis forms an angle ω_1 opening dorsally and pointing downwards (fig 2) in relation to the shaft The cortical shell of the neck is as thin as paper at its head end As the shaft is approached the cortical bone increases its thickness gradually In the superior part of the neck the increase is small but in the inferior part, the thickness increases considerably and is maximum where the major axis intersects the cortical bone Therefore in a section through the major axis the cortical bone is strongest in the inferior part It is of interest to note that a newborn femur has cylindrical neck and during growth the elliptical form develops

To be able to understand the design of the upper femur and its relationship to the forces acting on the bone the angles formed by the neck with the femoral shaft must be known This presupposes that the axes and the planes used to determine the angles have been defined. Fig 1 shows the axes and the planes according to Billing and Backman Their definitions are used in this study The OH line represents the cervical axis This axis

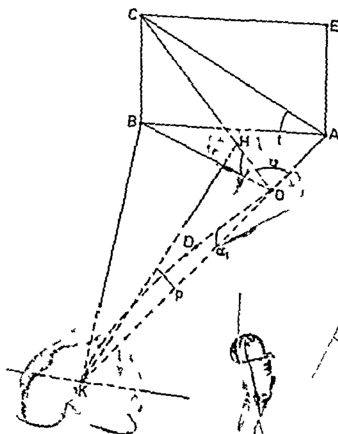


Fig 1 *The geometrical skeleton of the femur illustrating applied angles and planes Backman (1957)*

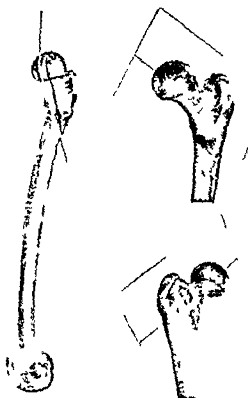


Fig 2 *The principle plane of the femoral head and neck Backman (1957)*

intersects the centre of the head H and at the point O the longitudinal axis ODK of the diaphysis The axis ODK similar to the femur forms a ventro convex curve As this is unsatisfactory in geometrical calculations Billing (1954) introduced what he called the ideal axis OK which is a straight line connecting point O with point K where the axis of the diaphysis perpendiculary intersects the line between the femoral condyles Using the above mentioned reference points two principal planes perpendicular to each other can be defined the frontal plane of the femur which coincides with the ideal axis and the condyle axis (plane ABK) and the sagittal plane of the femur which coincides with the axis of the diaphysis and the ideal axis (plane AEK) Their line of intersection line AOK together with the cervical axis OHC form a geometric system

The angle, formed by *the neck of the femur and the shaft the cervico-*diaphyseal angle is defined as the angle formed between the cervical axis OHC and the ideal axis AOK Its supplementary angle in figure 1 called u is on the average 54° The cervico-diaphyseal angle can also be defined as the angle formed by the cervical axis OHC and the proximal longitudinal axis of the femoral shaft OD This angle is slightly smaller than the angle formed by the cervical axis OHC and the ideal axis AOK, depending upon the magnitude and direction of the torsion angle

The cervical axis OH usually deviates forward to the frontal plane of the femur ABK and forms with this plane an angle v A plane through the ideal axis and the cervical axis AOKC is called the antetorsion or the anteversion plane The magnitude of antetorsion is given by the angle between the frontal plane of the femur AOKB and the antetorsion plane AOKC the angle t This angle is on the average 14° but the variation is great (Backman 1957)

If a plane is laid through the head and the neck of the femur coincident with the cervical axis and the major axis of the section area (fig 2) this plane will run through the middle of the fovea and bisect the head and the neck into two symmetrical halves It intersects the femoral shaft medially and distally just ahead of the lesser trochanter This plane called the *principal plane is coincident with the major axis of the section area* and forms a dorsally open angle ω pointing downwards with the cervico diaphyseal plane which is on the average 25° and with the antetorsion *plane (AKC in figure 1) an angle approximately 15°*

The variations of the cervico-diaphyseal angle the antetorsion angle and the principal plane under normal and pathological conditions have been *the subject of different mechanical interpretations* Opinions are *held by* some investigators that changes can take place in the design of bone in order to permit yielding to existing mechanical stresses while others claim

that changes occur because of yielding In addition to this, genetic factors also play a part.
In the newborn the cervico-diaphyseal angle is about 150° At the age of 18 months it usually has diminished to 140° and in adults it is about 130° In old people the cervico-diaphyseal angle may be noted to have been reduced to about 120°, (Lanz & Wachsmuth 1938) Humphrey (1888) and Walmsley (1914—1915) maintained that the cervico-diaphyseal angle will be larger if the femur is not subjected to load during growth Storck (1943) maintained that in paresis of the abductors, the centre of gravity will be centered over the head of the femur in gait and this would mean a more vertical direction of force. In order to resist this vertical direction of force the neck of the femur will turn to a valgus position
The ventral deviation of the neck beginning early in foetal life and increasing until delivery, probably depends on a torsion of the upper femur Consequently, the term version is less appropriate. At delivery the antetorsion is about 35° After delivery the torsion decreases and at the end of bone growth the anteversion has reached its final value, usually around 14° The variation, however is large and Backman (1957) in his series found the largest angle at 33° and the smallest at —13° Weszycki (1957) found a correlation between the degree of antetorsion the direction of the acetabulum and the size of the cervico-diaphyseal angle In coxa vara and a steep acetabulum there is slight antetorsion, while in coxa valga the acetabulum is more horizontal with a large antetorsion angle The fact that the antetorsion increases during the uterine life to become reduced after delivery has been the subject of both genetic and mechanical interpretations Le Damany (1903) believed that antetorsion is due to reduced space in the uterus and thus an adaptation to the squatting position of the foetus The author has based his assumption on experimental studies on animals Graf (1909) who made anatomical studies on the foetus doubts this explanation Graf pointed out that twins have no increased antetorsion, which would serve as a proof against Le Damany's theory Friedlander (1909), Brandt (1928) and Backman (1957) believe that the antetorsion depends on rotation in the femur during the foetal life Grunewald (1912) and Lange and Pitzen (1921) believe that the deviation is a combination of version and torsion Lange and Pitzen also hold the opinion that the cause of antetorsion as suggested by Le Damany ought to give retrotorsion instead The anteversion reduction during the growth period according to Morscher (1961) may also be due to the action of the internal rotators in gait Frankel (1960) utilizing load tests with vertical force direction found larger compressive stress in the posterior portion of the neck of the femur than in the anterior

Even if mechanical interpretations are justified no doubt the development is influenced also by genetic factors Martin (1959) has shown that different races have different antetorsion values Hultcrantz (Steindler 1955) found that races who usally sit in a squatting position have an increased antetorsion Altman (1924), Dega (1933) and Badgley (1943) believe that antetorsion is a genetic adaptation to the erect position and according to Dega, antetorsion gives increased stability in a standing position

The elliptical shape of the neck develops during adolescence Backman (1957) found that in small children the neck of the femur is cylindrical Before adult life the final shape and inclination of the neck are formed Whether this is a genetic phenomenon or an adaptation to mechanical stress or a combination of both has not yet been proved Bourgery (1832) and Wyman (1850) wrote that the increasing elliptical shape of the neck in a distal direction strengthens the resistance against vertical load Ward (1838) drew attention to the elliptical shape of the neck and to the fact that the major axis forms an open angle dorsally Lehmann—Nitsche (1895) and Strasser (1917) observed the inclination of the major axis of the elliptical cross section and Lehmann—Nitsche tried to measure the angle on specimens Grunewald (1918—1919) believed that the inclination of the principal axis was caused by muscular action Backman (1957) concluded that the inclination of the principal plane means that the force acting on the hip joint must be applied to the head from the ventral side This questions the direction of the force that Pauwels (1935) suggested The fact that the cortical bone is thickest on the inferior side of the neck in the principal plane supports this assumption

The internal structure of the proximal femur has also been the subject of mechanical analyses The spongiosa forms a trabecular network in which three main systems can be separated the medial, the lateral and the arcuate system

The purpose of the trabecular system is still discussed Usually the medial part is as Bourgery (1832) stated thought to take compressive strains The function of the arcuate portion is unclear, but it is often believed to take up tensile strains Storck (1943 1947) Farkas et al (1948) and Garden (1961) however believed that there are mainly compressive forces affecting the upper femur Hirsch and Brodetti (1956) have tried to measure the amount of force carried by the trabecular system and found that the spongiosa was responsible for 30 per cent of the resistance in the femoral neck Bourgery (1832) described the internal architecture of the femoral head and neck and claimed that trebecular system increases the strength of the bone He felt that the medial trabecular system carries the load acting on the head through the neck to the cortical layer of the femoral

shaft He also de cribed the two triangles formed between the different trabecular systems, the medial system later became known as Ward s triangle

Among others Langerhaus (1874), von Friedlander (1904), Farkas et al (1948), Tobin (1955), Rossi (1963 a) and da Silva (1964) have described and analysed the internal architecture of the upper femur Zschokke (1892) Walkhoff (1904) and Smyth (1958) pointed out that the trabecular system is found in some mammals Zschokke examined the trabecular system in horses and Walkhoff showed that the medial trabecular system is found in monkeys, although not so fully developed as in man He also analysed the architecture of the coxal femur end in the Neanderthal man and found that this race no doubt walked in an upright position The Neanderthal man lacked Ward's triangle The figures show that the principal axis of the neck is slightly inclined also in the Neanderthal man Smyth pointed out that animals who spend their lives hanging in trees lack the trabecular system in the hipjoint Zschokke, von Friedlander and Weidenreich observed that during uterine life there is a vascular network present in the bones whose structure, resembles that of the later developed spongiosa

Ward (1838), Wyman (1850) and Humphrey (1858) advocated the theory that the shape of the trabecular system depends on mechanical stress and that the arrangement of the spongy bone has been adequately adapted to these stresses Ward compared the upper femur end to a lamp bracket The triangular space formed in the frontal plane bears Ward s name Humphrey (1858) pointed out that the trabecular system may disappear in older people due to resorption

At a congress in Zurich in 1866, Meyer introduced a paper published in 1867 on the architecture of the spongiosa Similar to Ward, he described the direction of the spongious lamellae and the triangle Among the audience was Culmann who, dealing with graphostatics, pointed out that the structure of the lamellae and their direction were similar to the tress trajectories in a loaded Fairbairn crane Thus the Culmann—Meyer crane theory was developed, giving rise to both critical and favourable remarks Wolff (1870—1900) in agreement with the Culmann—Meyer theory established the so-called Wolff s law Wolff believed, similar to Culmann that the load on the head of the femur is approximately 30 kg Wolff based his theories partly on studies of pathological conditions A vital point in the Culmann—Meyer crane theory was believed to be the magnitude of angles under which the two trabecular systems cross each other If the trabecular systems really represent stress lines they should cross each other under an angle of 90° Prior to Meyer s paper, Ward (1838)

discussed the angle under which the bone lamellae are crossed Wolff and later Koch (1917), Pauwels (1948) and Rossi (1963) held the opinion that the angles almost were 90° Jansen (1920) on the other hand believed that the lamellae were not perpendicular and questioned whether pressure and tension were the only formative factors Pauwels (1948) was of the opinion that the trabecular pathways even if they are not stress lines, run in the same direction as the stress lines In his paper on functional adaption (1893—1896) Roux partly agreed with Wolff s law and introduced the expression functional adaptation Ritter (1888), Lorenz (1893) Bahr (1900), Ghillini et al (1902) and Kuntscher (1935 1936) delivered criticism against the Culmann—Meyer crane theory The criticism is based on the load conditions not being as simple as had been assumed by Meyer The shape of the bone is not entirely dependent on mechanical factors therefore genetic conditions must be considered Ritter, inter alia pointed out that it is necessary to know how the femur is loaded in order to decide whether the lamellae run in accordance with the stress lines Triepel (1904—1922) suggested that 1) formation of the spongiosa is an expression of a harmonious adaptation and 2) formation of the spongiosa is modified by the stress to which the bone is subjected The author dismissed Roux tests on models (Roux 1893) as he believed that these tests could be valuable only if the magnitude of the stress was known If the internal architecture is a sign of stress during load all forces including those of muscles must affect the orientation of the bone lamellae According to Grunewald (1912) the musculature is of greater importance in forming the femur than the body weight. The shape of the bone is therefore also dependent on the force created by separate muscles as they are applied to the bone Hanausek (1914) discussed the architecture of bones in relation to the compressive and tensile stresses which appear and Koch (1917) tried mathematically to analyse the architecture in order to determine the quantitative relations existing between structure and function Koch believed that good adaptation exists between the internal structure and the mechanical demands for each part of the bone The internal architecture of the bone gives a maximum strength with a minimum of material Haughton (1864), Jores (1920) Carey (1929) Murray (1936) Milch (1940) and Knese (1955 1956 and 1957) pointed out that the muscular forces probably exceed the static load, and that the dynamic stress is of the greatest importance to the architecture of the spongy bone. This opinion is also held by Jores and Murray who claimed that intermittent pressure stimulates the growth of bones According to Carey the trabeculae are arranged along the stress lines and arise through muscular activity The author also believed that the calcar femorale is caused by stress from

the hip flexors, the ileopsoas muscle and the gluteus maximus Milch maintained that the direction of the resulting force can be determined by analysis of the internal structure Gluckmann (1941—1942) believed that tensile stress provokes the formation of bone and affects the architecture Pauwels (1948, 1952, 1955 and 1958) on the basis of theoretical analyses and experiments believed that the trabecular system is built up in order to achieve a framework with minimum of material Bone apposition and resorption are caused by the magnitude of stress and, due to remoulding, the lamellae will have the same direction as though they were stress lines This means that the direction of the lamellae coincides with the pressure directed toward them If the stress conditions are altered, a new orientation will result. Stress on the epiphyseal cartilage may, according to Pauwels (1952, 1958) affect the bone growth Tensile stress on the epiphyseal cartilage would stimulate growth in length while thickness is determined by compressive stress Kummer (1955—1959) agreed with the theory that the skeleton is built up with a minimum of material in order to resist the required stress Furthermore, the upper femur can be regarded as a crane, but he disapproves of photo elastic tests on models for analysis of the trabecular system, as the magnitude and direction of the forces acting on the hip joint are unknown Smyth (1958, 1964) inquired about a quantitative method for measuring forces in the hip joint, as the muscular force is difficult to evaluate The author believed that bones can be formed to resist stress in the best possible way Garden (1961), on the other hand believed that the internal architecture of the femur cannot be determined by mechanical principles but that the structure arises through rotation and expansion from the shaft of the femur The spongy architecture depends on the expanding and rotating lamellae

Forces acting on the hip joint

The hip joint is surrounded by large muscles and strong ligaments The muscles and to a certain extent, the ligaments affect and complicate the calculations of the forces which act on the head of the femur Lack of knowledge about the magnitude and direction of these forces under differing circumstances has rendered the understanding of the biomechanics of the hip joint difficult In their analyses Meyer and Culmann assumed a load on the femoral head of about 30 kg Criticism has been directed against that low load because the authors were believed to have disregarded muscular effect However Meyer was aware that the force acting on the head of the femur is influenced by muscles Meyer (1849) pointed out that the joint cartilage is subjected to a pressure which is determined

both by gravity and muscular force Fick (1850, 1903), Milch (1947) and Debrunner (1958) pointed out the importance of muscular action on the hip joint

Many attempts have been made to calculate the resultant force which affects the head of the femur with regard to both size and direction.

Henke (1868 1869) Thomsen (1934) and Kuntscher (1936) pointed out that when calculating the force both gravity and muscular forces must be considered

Pauwels (1949 1950—1951) pointed out that the centre of gravity lies eccentrically in relation to the longitudinal axes of the bones and this may provoke heavy bending moments Muscles and ligaments increase the compressive forces but reduce the tensile stresses The long bones are composed of a minimum material

Koch (1917) calculated the dynamic load at double that of the static. In gait the static load on the head of the femur is about 80 per cent of the body weight and the forces acting against the head of the femur will be 1 6 times the body weight Koch pointed out, however that the femur may act as a shock absorber due to flexion in the hip and the knee. Grunewald (1918) believed that due to muscular action, the force acting on the hip-joint may reach 400 kg Storck (1931) tried to calculate the force which acts on the hip joint, with respect to both magnitude and direction The muscular force was calculated at double the body weight. The distance between the line of action of the centre of gravity and the centre of the head was calculated at 10 cm and the distance between the line of action of the musculature and the centre 5 cm. When standing on one leg this would mean a force of about 200 kg Pauwels (1935) on the basis of Fischer s works has calculated the magnitude and direction of the force acting on the head of the femur in one-leg support, two-leg support and during the stance phase in gait During one- and two-leg support insignificant muscular forces act in the horizontal plane and therefore the horizontal component of force is considered negligible. In gait a dynamic component is added in the horizontal plane, but the dynamic force in the frontal plane is predominant The author believes that insignificant muscular forces act when standing on two legs and the vertically directed force is equal to about 1/3 of the total body weight In one leg support, the muscular forces affect the magnitude and direction of the resultant The centre of gravity for the superimposed body weight is assumed to be 10 9 cm from the centre of the head, and the lever of the abductor muscle was estimated to be 40 mm The force acting on the head of the femur will be about three times the total body weight If during the stance-phase, consideration is given to the dynamic forces

the force will be 4½ times the body weight The horizontal component, which is dependent on the speed of gait, reaches its maximum at the beginning of the stance phase and amounts to about 73 per cent of the body weight It is then reduced to a minimum, and at the end of the stance-phase it again reaches a maximum of about 38 per cent of the body weight When using a walking stick the vertical force can be reduced to approximately 1 7 times the body weight

Inman (1947) calculated the force which acts on the head and believed that while standing on one leg, the force which acts against the head of the femur is 2 4—2 6 times the body weight

According to Cabot and Peralba (1952) the force on the femoral head in gait is equal to the fourfold body weight plus half of the body weight for a dynamic effect Knese (1955) believed that the pelvic resultant due to muscular forces in a superimposed body weight of 57 kg will be 395 kg which means that the force will be about 4 6 times the body weight Muller (1957) has calculated the force on the head of the femur in gait at 4 5 times the body weight, for a person weighing 75 kg which would mean a load of more than 330 kg The author further pointed out that the compressive stress in the hip joint is 3 times as great as the tensile stress depending on the direction of the resultant In two leg support the force according to Denham (1959), which acts on the hip joint is slightly greater than superimposed body weight and this is dependent on the muscular activity required to maintain equilibrium In standing position on one leg and a body weight of 68 kg, the joint will carry a vertical load of 204 kg and the vertical component of the abductor muscle force will be 136 kg If the neck of the femur is shortened even larger forces would occur and therefore in cases of arthroplastics the length of the neck should be maintained when possible If on the other hand, the head of the femur protrudes into the acetabulum the force will be reduced Abductor tenotomy would according to Denham, increase the load on the hip joint A medial displacement of the femoral shaft would not alter the force conditions For instance, walking with a stick may reduce the force from 204 kg to 54 kg Osborne & Fahrni (1950) and Soren (1963) also pointed out that by altering the levers the force acting on the hip joint can be changed Hackenbroch (1961) found that when standing on one leg the force on the femoral head is equal to the fourfold body weight minus the weight of the supporting leg During gait the resultant will correspond to the fourfold body weight due to dynamic forces Williams and Lissner (1962) calculated the force acting on the hip-joint in standing position on one leg at 2 4 times the body weight Hochman (1964) found that the force acting on the hip joint may amount to six times the body

weight Rossi (1963 b c) believed that when standing on two legs a force of 25 1 kg acts on the hip-joint at a body weight of 80 kg While standing on one leg utilizing the same body weight, the static force will be 276 1 kg and the muscular force 211 kg While walking the forces acting on the hip-joint are not as great as is usually assumed according to Rossi depending on the displacement of the centre of gravity during the stance-phase The author described the variation of the force during the stance phase and obtained a maximum value of 148 8 kg at a body weight of 80 kg Hauge (1965) pointed out that while standing on two legs the load will be half the overlying body weight plus a force of unknown magnitude This additional force depends on the muscles required to maintain equilibrium When standing on one leg the author calculated the load on the hip joint at 180 kg if the body weight was 60 kg

Due to the muscles the forces resultant will not be quite vertical Most previous calculations have been made only for the frontal plane Storck (1931) believed that the force in the standing position on one leg forms an angle of 15° with the vertical plane Pauwels (1935) believed that standing on two legs gives an entirely vertical force because the muscular components are insignificant Standing on one leg the force in the frontal plane forms a 16° angle with the vertical line Pauwels has also determined the direction of the horizontal component and found that in the horizontal plane it forms a dorsally open angle with the frontal plane of about 30° in the beginning of the stance phase and at the end of this phase it reaches a minimum angle with the frontal plane of about 2° This means that the femoral head is subjected to a load on its dorsal side Inman (1947) believed that the direction of force in one leg support is constant, irrespective of the position of the pelvis The force direction forms an angle of 10°—15° with the vertical line in the frontal plane which corresponds to the direction of the medial trabecular system The epiphyseal line runs perpendicular to the medial lamellae Since the resultant seems to follow these trabeculae no consequent shearing force will arise on the epiphyseal cartilage in the frontal plane During growth the abductor muscles alter their direction of action The direction of the resultant alters as well and the epiphyseal plate rotates so that it will always lie perpendicular to the direction of force When the abductor musculature becomes paralysed the load will be more vertical This is one reason why the epiphyseal cartilage remains in its horizontal position and gives valgus position Knese (1955) assumed that the pelvic resultant affects the head of the femur obliquely from above and then runs into a ventro caudal fibular direction Backman (1957) believed that the force in one leg support forms an angle of 28° with the longitudinal axis of the

neck This direction coincides with the direction of the medial trabecular system

The magnitude of the pressure arising on the head of the femur depends on the size of the contact surface It is difficult to assess this exactly, especially since one cannot be certain that the centre of the contact surface coincides with the point of force application According to Fick (1904) the medial upper portion of the head of the femur is subjected to the greatest pressure since its lateral upper portion lies outside acetabulum The author found this to be in accordance with Werner s (1897) calculations on the thickness of cartilage Little Lionel, Trueta (1948), Harryson, Schajowiz and Trueta (1953) and Trueta (1954) classified the head of the femur as containing a pressure-area and a non pressure area Buchet (1959) and Castaing et al (1960) pointed out that the anterior part of the femoral head is of great importance to the mechanics of the hip-joint, especially when the anteversion angle is large Together with Chevallier and Plisson (1963) Castaing reported a weak zone to be situated in the upper anterior part of the hip-joint While standing, the resultant runs along the longitudinal axis of the neck and forces the head of the femur upwards, inwards and forwards The maximum load will according to the authors, be carried by the anterior upper quadrant of the acetabulum

Stress and strain in upper femur

Many attempts have been made to determine stresses and strains in the femoral neck, when loaded Merkel (1874) pointed out that the proximal femur must carry a heavy load under an unfavourable angle Merkel believed that analyses usually are applied to one plane only, and this is a disadvantage Due to the anteversion of the femoral neck the force acting on the head will attempt to break the neck of the femur in the ventral direction and not in the longitudinal direction as Meyer and Wolff have assumed This means that the most stressed areas are the posterior and anterior portions of the femoral neck

Attempts have been made to quantitate stress by means of the stress coat technique photo-elastic model studies and strain gauges As bone is a heterogeneous substance the relation between stress and strain is rather complicated Many investigators are aware that these tests give only limited information

Roux (1895) carried out load tests on a rubber model which had been treated with paraffin Triepel (1904) criticized Roux investigations and mentioned that no conclusions can be drawn when the force direction is unknown

Kuntscher (1935 a b) carried out stress coat investigations on femurs which were subjected to dynamic loading under different inclinations of the femoral shaft. The same stress was obtained by different experiments The stress lines had a different course on the front of the femur as compared to the back, a phenomenon ascribed to the presence of the calcar femorale (1936) The author used a mirror extensometer for the measurement of bone deformities He pointed out that due to the heterogeneous nature of the bone, stress could not be mathematically calculated Milch (1940) carried out stress analyses by means of models manufactured from thin Catalin plates The experiments were carried out in two dimensions but the author believed that three dimensional experiments would be of greater value During the experiments stresslines were obtained corresponding to various trabecular systems by loading the model in abduction- and adduction positions. The author pointed out the difficulty of assessing the muscular forces in the hip-joint since the magnitude varies from time to time Pauwels (1948 1950 1951 and 1955) carried out photo-elastic model experiments and the results obtained showed that the architecture of the bone is adapted to the stress to which the bone is subjected, and that bone is formed from a minimum of material Pauwels furthermore believed that the muscles serve to eliminate the bending moment The musculature is *required to develop its entire force when needed to equalize compressive* and tensile stress Evans and co-workers have made numerous strain analyses in the upper part of the femur Stresscoat studies have been performed using a vertical load and with the intracondylar plane horizontal or with a laterally open angle of 3° (Evans 1948 Pedersen Evans and Lissner 1949) Evans Pedersen and Lissner 1951 Lissner and Evans 1956 and Evans 1962)

Rauber (1876) Koch (1917) and Knese (1956 1957) pointed out the impaired resistance to tensile stress of bone and this has been verified by Evans and co-workers Furthermore it was noted that the speed used to apply the load is of importance to the bone s resistance. This has also been proved by Mc Elhaney (1965) and Sedlin and Hirsch (1965) In a paper by Evans and Charles (1957) dealing with stress-coat technique, the so-called splitline method was used According to Evans and King (1961) spongy bone shows a poor resistance to load, but has good energy absorbing capacity Jakobsson (1954) carried out photo-elastic model tests where stress distribution in normal and dysplastic hip-joints were studied Kummer (1955—1956 1959) carried out stress coat experiments on plexiglass models Fessler (1957) found in photo-elastic studies on a hip-joint model stress lines that resembled the trabecular system. These experiments were carried out on one plane only Hirsch and Frankel (1960 1961) performed

analyses with the strain gauge and the stress coat techniques The abductor muscles were found to cause compression in the upper portion of the neck and the distribution of stress in the femoral neck was affected

Measurement of dynamic forces during gait

Determination of forces acting on the femoral head in walking is often combined with gait analyses It is often desirable to correlate the forces to the different phases of double steps

For a detailed history on gait analyses, reference is made to Weber (1836) and Steindler (1955) Besides static load and muscular forces, dynamic forces are also involved in gait These are determined by the body mass and its acceleration Therefore, gait may cause a load on the hip joint which considerably exceeds the body weight The vertical force arising between the foot and the ground may be calculated but is complicated Fischer (1899 1904) determined this mathematically

Pauwels (1935) on the basis of Fischer s data calculated both the vertical and the horizontal dynamic force acting on the hip joint

An apparatus constructed to record the forces developed between the foot and the ground will facilitate the measurements The vertical force which acts on the hip joint should in relation to time coincide during the stance-phase with the vertical force between foot and ground

The first attempts to determine the force between foot and ground in gait were made by Carlet (1872) and Marey (1873, a and b, 1883 1885, 1894) Quenеu and Demeny (1888) performed similar measurements The measuring apparatus was called a dynamograph and consisted of two air-filled pockets one placed under the heel and one under the fore foot By means of pressure variations the vertical force component between foot and base was determined as well as the time of loading The diagrams of the anterior and posterior pockets were drawn The graph obtained is the same shape as those obtained when recording with the present electronic force-plates From the graphs the various phases of gait could be determined During measurement the vertical force did not exceed the body weight by more than 20 kg even in rapid gait Measurements were performed together with chronophotography In some cases the vertical force was less than the body weight during the stance phase The author believed that those cases where pressure exceeds body weight are dependent on the vertical acceleration of the centre of gravity Schwartz and Vaeth (1928) constructed a so called basograph for measuring forces between foot and base The design was abandoned and Schwartz and Heath (1932) introduced a pneumograph for recording these forces The design

was made of pneumatic cells fitted in the heels of specially manufactured shoes They were connected with a recording instrument and variations in pressure between foot and base were determined By letting the subjects walk on a controlled speed tread mill the walking speed could be determined Film recording was performed simultaneously In 1934 the pneumatographic design was dispensed with and replaced by an electrographic recorder which recorded both the total time of loading and contact time of the heel 5th metatarsal head and the great toe (Schwartz et al 1934 1936, 1937 1941 1949 and 1964) Elftman (1938—1939) improved the technique and built a mechanical force plate which served to determine three force components between foot and ground Measurements were carried out with simultaneous photography Eberhart (1947) published a report from the University of California which dealt with studies on gait Measurements were made with electronic force plates Early studies used a force plate constructed by Northrop Aircraft Corp but later Eberhart s own design was employed The forces arising between foot and ground are obtained in electronic force plates by means of strain gauges All force components can be recorded Eberhart and Inman (1949) Elftman (1949) Cunningham and Brown (1952) Saunders Inman and Eberhart (1953) Cunningham (1958) reported measurements with force plates

For gait studies of horses Bjork (1958) designed a force plate mounted in a horseshoe which determined the force arising between the ground and hoof under different conditions Wetzenstein using a similar technique (1964) mounted a power plate in the heel of a man s shoe and determined the load conditions of the heel in gait.

Marks and Hirschberg (1958) and Drillis (1958) used force plates to analyse the forces between the foot and ground under normal and pathological conditions In order to study friction on different floor surfaces by means of force plates measurements were performed inter alia by Harper Warlow and Clarke (1961) and Carlsoo (1962) The first mentioned authors have, in some cases recorded a vertical load less than body weight during the entire stance phase Contini (1964) worked with electronic force plates and believed that in rapid gait the vertical force has a certain maximum value which is not exceeded

II Design of the measuring prosthesis

Introduction

Ingelmark and Blomgren (1948) have designed an apparatus for pressure-measurements in joints under vital conditions for experiments in animals. No attempts have been made to measure forces in the hip-joints of human beings in vivo. In the literature chapter earlier attempts to determine the magnitude and direction of the forces acting on the femoral head under static conditions have been reported. Attempts to calculate the dynamic components have been made by Pauwels (1935). One drawback with theoretical analyses is that they must be carried out for a certain position in the hip joint, for example, standing on one leg, or with a known degree of flexion in the hip joint. During the standing position on one leg, the line of action of the body weight does not pass through the centre of the head of the femur, the upper part of the femur is subjected to moments, and to maintain the balance the muscles must exert a counter force on the joint. From the two forces — the weight and the muscular force — the force acting on the head of the femur is then determined by applying the parallelogram of forces. This resultant is then resolved into two perpendicular components. In flexion the position of the centre of gravity in the leg and the direction of the muscular pull must be known if the force is to be determined.

Although under certain circumstances the force acting on the hip joint can be determined to a fair level of accuracy by this method, it has certain shortcomings. For instance, the calculations are usually made for only one plane, that is to say only the components P_x and P_y in fig. 3 are determined.

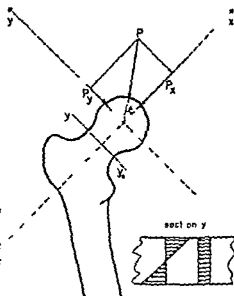


Fig. 3. *A force P acting on the femoral head can be resolved into two perpendicular components P_y and P_x. In a section through the neck the strains caused by the forces are indicated.*

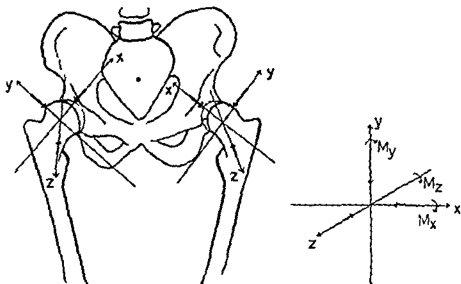


Fig 4 *A three dimensional co ordinate system is applied to the femoral head and neck with origin at the center of the head and the x axis along the longitudinal axis of the neck The force on the head can be resolved in three orthogonal components acting along the axes The components are nominated in accordance with the axes they act along and the moments set up in the neck in accordance with the axes they act about*

The results will be valid only in the cases in which the force acting in the third plane — the horizontal component — is negligible If the values are to be accurate it is necessary to perform the calculations for certain situations — for example with the subject standing on one leg when the horizontal component is small and the force acting is large By adding a value for the dynamic effect the force acting during the stance phase in walking would be obtained

Though one leg support is a position in which the upper end of the femur is subjected to the greatest static force there are others more common in which it is of interest to know the forces acting on the head of the femur In for instance flexion of the hip joint the components P_x P_y and the horizontal component P_z should be more equal in magnitude and then the application of the parallelogram of forces in one plane will not give very accurate values

In flexion and extension or abduction and adduction it is difficult to determine exactly the direction in which the muscles pull and the length of the moment arm and this introduces a factor of unreliability in the calculation of the forces acting on the hip joint

More reliable results would be obtained if the force acting on the femoral head is determined in relation to a three dimensional co-ordinate system (fig 4) If three orthogonal components are to be measured simultaneously

they are measured along the x- y- and z-axes, and the forces acting along these axes are called P_x, P_y and P_z respectively If the co-ordinates are placed as in fig 4, with origin at the center of the femoral head and the x axis along the longitudinal axis of the neck, P_x will cause compressive strains in the neck, while P_y and P_z will cause bending in the neck The bending moment resulting from P_y occurs about an axis parallel to the z axis, and that from P_z about an axis parallel to the y axis Accordingly these moments are called M_z and M_y respectively

Forces acting on the hip-joint are usually not static, instead there is, from the mechanical aspect, a relatively slow dynamic development, the point at which the force acts on the head of the femur changing its position as the head moves in the joint. Since one component of the force P acting on the hip-joint is the muscular force the direction at which P acts on the head alters as the end of the femur moves in the acetabulum It is almost impossible to calculate the motion of the point of action of the resultant force over the surface of the head in for example, the different stages of walking — the swing phase and the stance-phase

If it were possible to measure these forces directly on the living subject more reliable information would be obtained and the dynamic course of events could be recorded

The force acting on the head of the femur causes stresses and strains in the neck of the femur (fig 3) In theory therefore, it would be possible to determine the stress by means of strain gauges applied to the neck of the femur, and from the recorded values to calculate the components of the force acting on the head In practice, however this is not feasible, for problems arise in applying strain gauges under vital conditions, for instance it is difficult to attach the gauges stably to the moist and slightly greasy surface of the bone. The conducting material must be insulated against moisture, and measures must be taken to avoid any toxic effect of the cement

Since the physical properties of the bone differ not only from one person to another but also intraindividually, according to the local conditions, (Carothers et al 1949, Evans and Lebow 1951, Evans 1957 and 1964, Forsblad 1959 Hirsch and Evans 1965, Sedlin 1965), the measurements are not reliable generally Bone is a heterogeneous material and Hooke s law is not obeyed completely Since also the geometry of the neck varies, accurate measuring values cannot be obtained unless calibration can take place by applying a known load, and this is impossible in experiments under vital conditions This method, however, can be applied to model tests on autopsy specimens (Hirsch and Frankel 1960 1961, Frankel 1960)

Since metal is a highly suitable material as a support for a strain gauge

and the head and neck of the femur can be replaced by a metal prosthesis, it was considered that the required forces might be determined by placing such gauges in a prosthesis that could be inserted in the upper end of the femur The results thus obtained are not directly applicable to physiological conditions but the method was believed to give new information on the hip

The commercially available hip prostheses are not suitable in their existing form for the construction of a prosthesis of the type desired for most of them have no neck part, and this is indispensible because the essential feature of the method is that the forces acting on the hip joint are determined from stresses set up in the neck part If the measurements are to be accurate the dimensions of the prosthesis must be exact and the strain gauges, which are not well tolerated by the tissues must be applied so that they cannot come into contact with the body fluid The best way of ensuring this is to place the gauges inside the prosthesis

In the design of a prosthesis to replace the upper end of the femur and to serve as part of the measuring system, account must be taken of the manner in which the signals are to be transmitted from the prosthesis to the recording unit Telemetry would have been the best and the most elegant method but it was ruled out in the present case on practical and financial grounds The signals had therefore to be transmitted by wires in the conventional way Before the design dimensions and selection of the material for the prosthesis could definitely be settled certain assumptions had to be analysed and definitions established

Definitions of forces acting on the measuring prosthesis

In the design of a prosthesis of the type proposed with built in strain gauges the following theoretical assumptions must be made

Let P be the force acting on the prosthetic head (fig 5) This force unknown in magnitude as well as direction is to be determined Force P can be resolved into three mutually perpendicular components P P_y and P parallel to a co ordinate system that is fixed in relation to the prosthesis The origin of these co-ordinates is placed at the centre of the head the x axis coincides with the longitudinal axis of the neck the y axis perpendicular to this in the frontal plane and the z axis perpendicular to the other two axes (fig 5) The advantage of recording the forces to a co ordinate system which is fixed in relation to the prosthesis instead of in relation to the co-ordinates of the body is that the direction of the force is obtained in relation to the proximal femur irrespective of its position in the joint

In the absence of friction the force P would act through the mid point of the head when friction is introduced P no longer acts at the mid point, but the displacement is negligible, and in most cases it can be assumed for the purpose of the calculations that P does act through the mid point.

The component P_x gives rise to a compressive force in the neck of the prosthesis and the components P_y and P_z give rise to the moments M_z and M_y about the z and y axes, respectively Even around the x axis there is a moment, due to friction called M_x. M_z and M_y cause compressive as well as tensile strains in the neck, M_x torsional strains

By placing measuring receptors at a known distance from the point of action of the components, which is, the mid point of the head, the strain resulting from the force components can be recorded and the forces deter

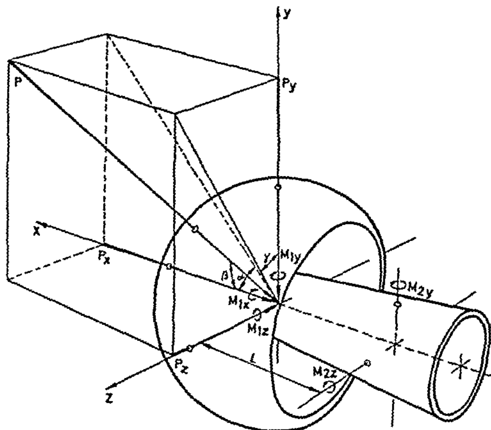


Fig 5 *The head and neck of the measuring prostheses The required force P is resolved into three orthogonal components The moments and the angles necessary to determine the direction of the forces are indicated*

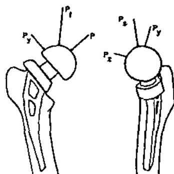


Fig 6 *The measuring prosthesis applied to the proximal femur with the force components indicated P_f=projection of the force P in the frontal plane P_s=projection of the force P in the sagital plane*

mined One advantage of this procedure is that the components P_x P_y and P_z are recorded The magnitude of the resultant P is given by the expression

$$P = \sqrt{P_x^2 + P_y^2 + P_z} \tag{1}$$

The angles under which P acts on the prosthesis are obtained by trigonometry Two of these angles, α and γ have been chosen (fig 7) as representative of the direction of the forces namely those formed by the components P_x and P_y and the projection of resultant P in the frontal and sagittal planes P_f and P_s respectively These angles are given by the expression

$$\tan \alpha = \frac{P_y}{P_x} \tag{2}$$

and

$$\tan \gamma = \frac{P}{P_y} \tag{3}$$

The angles α and γ give the direction of the force components The direction of the resultant force P is determined by those angles and the angle β in fig 5 This angle is formed between the resultant force and its component P_x and is given by the expression

$$\cos \beta = \frac{P_x}{P} \tag{4}$$

If forces are required in relation to the co-ordinates of the body, consideration must be given to the position of the upper end of the femur in the acetabulum

As mentioned earlier, the force P will not act through the mid point of the head due to friction If the coefficient of friction is to be determined

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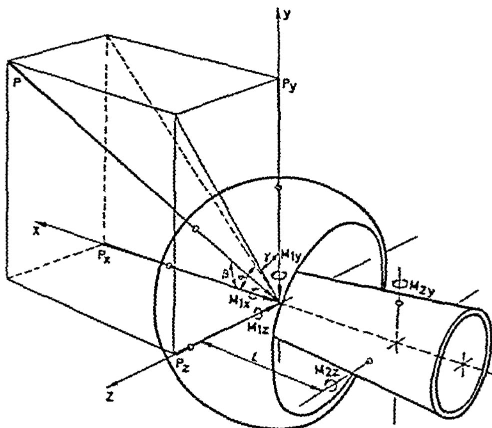


Fig. 5. The head and neck of the measuring prostheses. The required force P is resolved into three orthogonal components. The moments and the angles necessary to determine the direction of the forces are indicated.

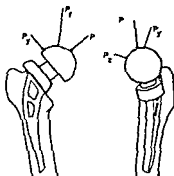


Fig 6 The measuring prosthesis applied to the proximal femur with the force components indicated P_f = projection of the force P in the frontal plane P_s = projection of the force P in the sagital plane

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If forces are required in relation to the co-ordinates of the body consideration must be given to the position of the upper end of the femur in the acetabulum

As mentioned earlier the force P will not act through the mid point of the head due to friction If the coefficient of friction is to be determined

the combined effect of normal and tangential stresses can in general not be strictly described by a single resultant force One correct description would be as one force and one moment, both acting off the center of the head and having 3 components each

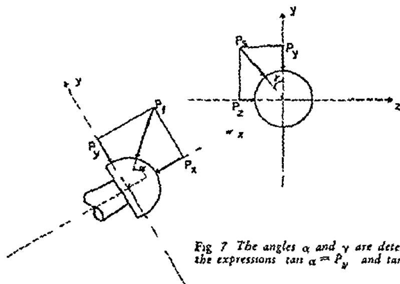


Fig 7 The angles α and γ are determined by the expressions $\tan\alpha = P_y$ *and* $\tan\gamma = P_z$

As an alternative way of description, two components of the moment can be explained as the result of a displacement of the resultant force from the center point This description has the drawback that the displacement can be very large if friction forces are great, which is probably not the case The stresses due to moments acting in a section through the centre of the head must be recorded if the coefficient of friction is to be determined or if displacement from the midpoint is not negligible for the determination of the force P Strain gauges have therefore been placed in two neck sections, one section perpendicular to the longitudinal axis of the neck through the mid point of the head, section I, and the other, section II, at a known distance, L, from section I (fig 5) The moments recorded in the respective sections are therefore further indicated by the suffixes 1 or 2, such as M_{1y} for section 1 and $M_{\ y}$ for section 2 In selecting positive or negative signs for forces and moments some difficulties might occur since the same force may have different signs for a left and a right hip The problem has been solved in such way that if the prosthesis is inserted in a right hip and regarded as in fig 7 the forces acting along the x and y axes towards the mid point are given positive signs Regarding the z axis for practical reasons the force acting along the negative z axis that means coming from the ventral side toward the origin has

been defined as positive If the prosthesis is inserted in a left hip the signs for the force along the x axis would be changed and this is not desirable Thus, the force along the x axis is called positive if it acts in medio lateral direction along the y axis the force is positive when acting in cranio caudal and positive along the z axis in ventro dorsal direction According to the same principle the signs for moments M_y and M_z are obtained The torsion moment was recorded only in prosthesis 2 and is positive for rotation in the direction indicated in fig 5, the prosthesis seen ventrally in the left hip

If the resultant force P acts through the centre of the prosthetic head components P_y and P_z are obtained by dividing the moments recorded in section 2 resulting from the components respectively, by the moment arm

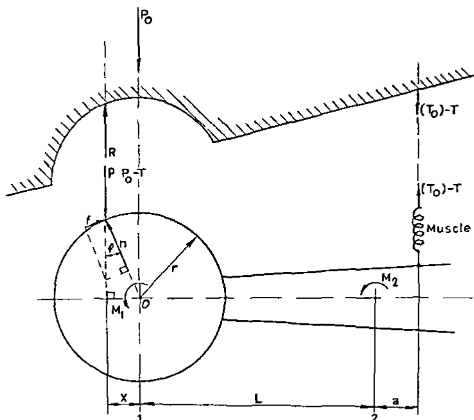


Fig 8 *Due to friction a force P_0 is displaced from the origin if the muscular force is changed by an amount T The force of reaction R will result from the normal force n and the friction force f*

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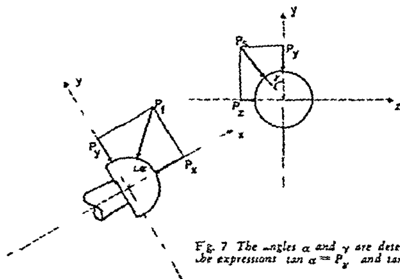


Fig. 7 The angles α and γ are determined by the expressions $\tan \alpha = P_y$ and $\tan \gamma = P_z$

As an alternative way of description, two components of the moment can be explained as the result of a displacement of the resultant force from the center point. This description has the drawback that the displacement can be very large if friction forces are great, which is probably not the case. The stresses due to moments acting in a section through the centre of the head must be recorded if the coefficient of friction is to be determined or if displacement from the midpoint is not negligible for the determination of the force P. Strain gauges have therefore been placed in two neck sections, one section perpendicular to the longitudinal axis of the neck through the mid point of the head, section I, and the other, section II at a known distance, L, from section I (fig 5). The moments recorded in the respective sections are therefore further indicated by the suffixes 1 or 2 such as M_{1y} for section 1 and M , for section 2. In selecting positive or negative signs for forces and moments some difficulties might occur since the same force may have different signs for a left and a right hip. The problem has been solved in such way that if the prosthesis is inserted in a right hip and regarded as in fig 7 the forces acting along the x and y axes towards the mid point are given positive signs. Regarding the z axis, for practical reasons the force acting along the negative z axis that means coming from the ventral side toward the origin, has

Photo-elastic experiments

On the basis of previously presented assumptions and theories in order to judge the practical application of the measuring prosthesis photo-elastic model studies have been carried out A model of the proximal femur was made of epoxy resin E The neck part had the shape of a parallelepiped 18×10×40 mm in size From these studies information has been obtained about the suitable location of strain gauges For instance corners radii or fillets will have a disturbing effect and the strain gauges must be placed so that these disturbances will not affect the measuring signals The neck of the prosthesis must be sufficiently long to permit placing the strain gauges within undisturbed areas For anatomical reasons however the size of the neck is limited

A cast of Araldite E was made of the upper end of the femur and a measuring section with parallel surfaces was cut out The stress distribution along the measuring section could be seen when loaded Information was obtained as to the stress concentration at the fillets and the extent of these stress raising areas It was thus possible to determine the position of the strain gauges and the desired length of the measuring section With a 40 mm long neck and a fillet radius of 2 5 mm a highly stressed area of approximately 8 mm in length occurred proximally and distally in the neck If the strain gauges have an active length of 3 mm a distance of 20 mm may be allowed between the measuring sections

Based on data obtained from the photo elastic tests a pilot model of light metal Svenska metallverken 6958, was made It was provided with strain gauges placed within the limits obtained by means of the photo-elastic tests The model was subjected to numerous static loads and strains were recorded at the various measuring points After analysing the obtained data, it was found that a static force could be determined as to magnitude direction and position with an accuracy of 1—2 %

Choice of metal

It was desirable to have a neck part which would, when subjected to forces of the magnitude expected give sufficiently large deformations in the material so that adequate signals could be obtained from the strain gauges One condition was also that the material was strong enough to stand actual stresses in spite of small section thickness

At present three types of metals are used for orthopaedic implants

1) Commercially pure titanium 2) Stainless steel of the 18—8 Mo type
3) Cobalt chromium alloys

Titanium was not used because of its comparatively low resistance to

L that is the distance between the centre of the head and section 2 (fig 5) Thus obtaining the expressions

$$P_y = \frac{M_z}{L} \qquad (5)$$

and

$$P_z = \frac{M_y}{L} \qquad (6)$$

since the forces are directly proportional to the measured moments The force component P_x which does not cause any moment is determined directly from the strains resulting from the force

The above formula does not apply if consideration has to be taken of the displacement from the mid point of the head of the resultant force P due to friction Fig 8 shows how the friction moment can be described as if the resultant is displaced from the origin if the muscular force is changed by an amount T The force of reaction R, resulting from the normal force *n* and the friction force f, will also be displaced and balance will be maintained until the friction force is fully established As long as equilibrium exists the following will apply

$$P - R = O \qquad (7)$$

and

$$T(a+L) - R \quad x = O \qquad (8)$$

Moment section II will give the expression

$$M_s = P(x+L) \qquad (9)$$

In order to determine P, the friction moment must be subtracted Taking the origin as the moment centre will give

$$M_1 = P \quad x \qquad (10)$$

By subtracting the expression

$$M_1 = P \quad x \qquad (11)$$

from the expression

$$M = P(x+L) \qquad (12)$$

the following is obtained

$$P = \frac{M - M_1}{L} \qquad (13)$$

Similarly the components are obtained from the expressions

$$P_y = \frac{M_z - M_{1z}}{L} \qquad (14)$$

$$P_z = \frac{M_y - M_{1y}}{L} \qquad (15)$$

The Teflon cable and the leads must be removed when the measurements are finished The Teflon cable could be pulled out and the leads were to be cut off close to the prosthesis and removed Any part of the leads that remain would come into contact with body fluid but due to the quite negligible quantity of foreign material, there was considered to be little danger of toxic effects

Design and dimensions of measuring prosthesis

Prosthetic head

The size of the prosthetic head should accurately fit the acetabulum In ordinary arthroplastic operations in the hip joint, different sizes of prostheses are available As a limited number of measuring prostheses were to be manufactured the head of the prosthesis was made 1⁷/₈ or 47 2 mm in diameter which according to our experience is the size most commonly used The prosthesis has been made somewhat larger than half a sphere To obtain enough length in the neck part — the available space is limited for anatomical reasons — the head was made hollow In addition this enabled the centre of the head to be placed 10 mm into the neck and strain gauges could be applied in a section through the centre of the prosthetic head

Neck of prosthesis

Recording of strain takes place in the neck part by means of applied strain gauges To obtain satisfactory measuring accuracy the neck of the prosthesis must be rather long Available space from an anatomical viewpoint appears to be about 40 mm Rigidity against radial deformations in the front part of the neck is obtained by a sturdy flange This flange is threaded and has fittings for the prosthetic head As the neck is hollow and the strain gauges placed on the inside it must be possible to pull out the wires The flange was made with a hole for the nipple and lead wires

To fit into the stem of the prosthesis the neck part was provided with a cone shaped shank with internal thread By such means it was possible to obtain a joint with zero slackness and high load bearing capacity and with a minimun neck length The base of the neck tube was closed by a metal plate to prevent radial deformations

For technical reasons the included angle between the axis of the neck part and the stem was made 120° This is 6° less than the average cervico diaphyseal angle (Backman 1957) In the hip the angle between the prosthetic neck and stem will represent the angle between the neck and the longitudinal axis of the proximal femur The true cervico diaphyseal

angle however, is formed between the neck and the ideal axis of the femur and this angle is somewhat greater The difference is partially dependent on the magnitude of antetorsion the prosthesis will have in the hip The internal diameter of the neck was determined on the basis of the installation of the train gauges 16 mm is a suitable diameter, both as regards the glueing of the gauges and the anatomical conditions

The section thickness of the prosthesis depends on the strength of the material and the force expected to act on the head Providing force P acts through the centre of the prosthetic head the moments caused by the vertical and horizontal components P_y and P_x are obtained in a section through the prosthetic neck from expressions

$$P_y = \frac{M_x}{L} \qquad (16)$$

and

$$P_x = \frac{M_y}{L} \qquad (17)$$

where L is the distance between the mid point of the head and the measuring section in the prosthesis designated section 2

For the purpose of dimensioning these expressions can be given the formula

$$M_x = L \cdot P \sin \alpha^* \qquad (18)$$

and in bending according to Hooke s law

$$LP \sin \alpha = E \cdot W_b \cdot \varepsilon_{b} \cdot \frac{D}{d} \qquad (19)$$

where E is the modulus of elasticity and ε_{b} = the bending strain of the inner surface in the sectional cross section

Further

$$W_b = \frac{\pi (D_2^4 - d^4)}{32 \; D} \qquad (20)$$

where D = major sectional diameter

and d = minor sectional diameter

If a strain of $\varepsilon_{b} = 1$ ‰ occurs for a force P of 400 kp acting on the head and $\alpha = 60°$ and $\gamma = 0$ a deflexion of the galvanometers of 12 cm takes place Thus $\varepsilon_{b} = 1$ ‰ has been considered suitable and in that case D = 18 65 mm and thickness in section 2 t = 1 33 mm The thickness of the prosthetic neck was settled to 1 4 mm in section 2

If no friction occurs in the joint force P acts through the centre of the head and the moments in section 1 M_{1x} and $M_{1y} = 0$ To determine the thickness in this section calculations must be based on the smallest

Of course this formula applies only if $\gamma = 0$

section thickness which is obtained next to the fillet 8 mm in front of section 1 Analogously with the expression for section 2 for a section next to the fillet is obtained

$$-8\ P \sin \alpha = E \quad W_{bf} \quad \varepsilon_{bf} \quad \frac{D_f}{d} \tag{21}$$

where ε_{bf} is equivalent to the bending strain of the inner surface in the cut and

$$W_{bf} = \frac{-(D_f^4 - d^4)}{32 \quad D_f} \tag{22}$$

If D_f = external diameter of the cut and if $\varepsilon_{bf} = 1$ ‰ $P = 400$ kp and $\alpha = 60°$ D_f must be 17 2 mm and t_f = 0 6 mm
The thickness of the prosthetic neck next to the fillet was fixed at 0 7 mm With 0 7 mm at the fillet and 1 4 mm at section 2, in section 1 the thickness t_1 = 0 9 mm is obtained
The gauges measuring the axial force P_x was placed between the two sections at a distance of 8 mm from section 1 In this section the thickness t_3=1 1 mm and A_3 (cross section area) = 59 2 mm
Strain due to the axial force is obtained from expression

$$\varepsilon_{p3} = \frac{P \cos \alpha}{A_3 \quad E} \tag{23}$$

If P = 400 kp and $\alpha = 60°$ ε_{p3} = 0 165 ‰
With the dimensions set forth above the maximum permissible loads have been calculated With regard to static loads the greatest stress concentration will occur at the lateral fillet The nominal stress in this cut is obtained according to

$$\sigma\ nom_f = \pm \frac{P \sin \alpha (L + 7\ 5)}{W_{bf}} - \frac{P \cos \alpha}{A_f} \tag{24}$$

where A_f = cross section area and

$$W_{bf} = \frac{-(D_f^4 - d^4)}{32 \quad D_f} \tag{25}$$

where D_f = major diameter of cut and d = minor diameter of the cut If P = 400 kp and α 60° $\sigma\ nom_f$ = —28 5 kp/mm is obtained
For the fillet in question a form factor of 1 6 can be given, which means that $\sigma\ max_f$ = —45 5 kp/mm
With the given strength data local plastic creeping will occur in the fillet for static loads exceeding 570 kp and fractures for static loads exceeding 920 kp

The strength decreasing effect of the fillet will however, be eliminated by the stress adjustment occurring due to creeping of the material, so that fractures will not occur unless the static loads are considerably greater than the maximal loads indicated above
The material has a minimal fatigue strength of ± 25 kp/mm² amplitude for a lifetime of 10^7 cycles of loading and is increased by local stress adjustment
Since it is mainly a question of pulsating loads an upper limit of about 40 kp/mm² is permissible If a deduction of 20 % is made for the strength decreasing factors a fatigue strength of up to 32 kp/mm² is permitted As the material has no notch brittleness the margin of safety should be sufficient if a notch fatigue factor of 1 2 is considered Fractures due to fatigue will not occur until loads exceed 390 kp

Stem of prosthesis
The only difference between the stem of the measuring prosthesis and that of a conventional Moore prosthesis is its somewhat larger dimensions

The prosthesis
The measuring prosthesis has three parts the head the neck and the marrow space anchorage (fig 9)
In addition there were internal gauges from which leads passed out through a nipple sunk into the flange of the neck At the distal end the leads, 22 cm long were joined to a multi pole female contact built into a hermetically-sealed metal cylinder The passage of the leads through the nipple was sealed with resin The leads, insulated separately, also passed through a Teflon collar threaded on the nipple In order to give the cable formed by the wires better rigidity strips of Teflon were placed between the various wires In this way there was less risk of the wire-insulation cracking The female contact contained toxic material and was placed in

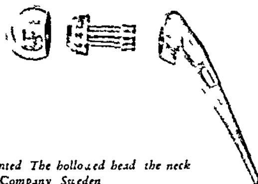


Fig 9 *The measuring prosthesis unmounted The hollowed head the neck part and the stem can be seen Bofors Company Sweden*

a hermetically sealed cylinder This cylinder was made of the same mate rial as the prosthesis Also the nipple of the cylinder was sealed with resin

The wires going out from the prosthesis were removed when the measure ments had been completed It is desirable to remove the wires as close to the passage in the prosthesis as possible The nipple and the threaded-on Teflon collar were encased in a steel sleeve glued to the prosthesis The purpose of the steel sleeve was to prevent cracking of the wires as they pass out from the nipple to improve the sealing and to serve as a sharp edge to cut the wires when they were to be removed By pulling the wires against the sharp edge of the sleeve it was hoped that they would be severed In practice this did not occur and an incision had to be made to remove the wires

The threaded units of the prosthesis were fixed by means of resin For gluing the strain gauges wires the lateral threaded unit and nipple a resin of the Araldite XV type which was heat cured at 150° was used An Araldite D type resin was used as adhesive for the strain gauges for component M_x The mounting of the prosthetic head which was the last phase of the installation was carried out with Araldite D with Hy 956 activator As this is a room temperature curing adhesive it was unnecessary to heat the measuring prosthesis during the hardening process With a high temperature curing resin it is very difficult to obtain an absolutely tight unit because the air in the measuring prosthesis expands with heat and forms canals in the glue joint

The main parts of the prosthesis were tested with ultra sound for cracks To obtain the overall surface finish the head and the stem were electro polished Fig 10 shows the measuring prosthesis mounted in its finished condition Fig 11 is an outline drawing of the prosthesis giving dimensions

Measuring receptors and measuring principles

In the first prosthesis Hottinger strain gauges of type 3/120 FB1 have been used for recording the components M_1 M M_{1y} M_y and P_x The gauges have an active length of 3 mm and a resistance R of 120 ohm The gauging factor g is 1 99 ± 1 %

The second prosthesis has been provided with Baldwin strain gauges of type AB 11 with a resistance of 120 ohm and a gauging factor of 1 90 ± 1 % The active length of the gauges is 3 mm For component M_{1x} another strain gauge of Budd manufacture type C6 121 R_{Ω} has been used Its resistance is 120 ohm the gauging factor 1 99 ± 1 % active length 3 mm Theories concerning measuring with strain gauges can be found in litera

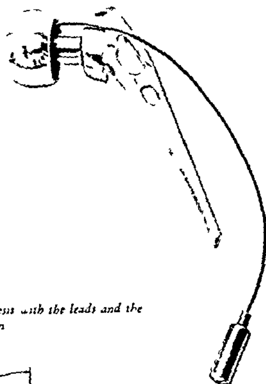
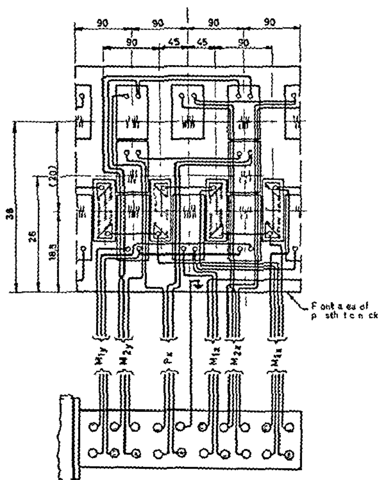


Fig 10 *The mounted measuring prosthesis with the leads and the contact house Bofors Company Sweden*

Fig 11 *An outline drawing of the measuring prosthesis Figures in mm when not indicated otherwise*

ture on this subject (e g *Mechanical Measurements* Beckwith and Buck 1961 *The Strain Gage Primer* Perry and Lissner 1962 and *Instr ument Transducers* Neubert 1963) The measurements are based on changes in resistance of the gauges which are connected in a Wheatstone bridge If one resistance is altered this will result in imbalance in the bridge and in a suitable way this can be recorded as a change of voltage of the bridge. For a Wheatstone bridge an imbalance must arise in proportion to the algebraic difference of resistance changes in any two adjacent arms and in proportion to the algebraic sum of resistance changes in any two opposite arms With strain gauges — strains cannot only be measured but through suitable coupling the recorded strains can be eliminated or enlarged Suitable placing of the strain gauges in the Wheatstone bridge



F g 12. *The coupling sc*l *eme of the prosthesis of case 2*

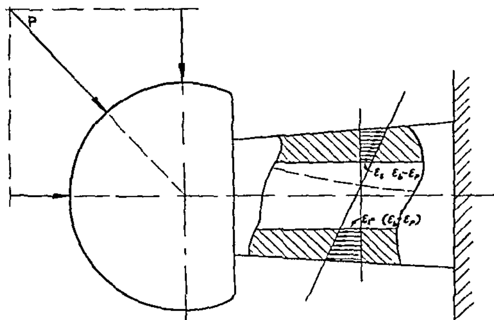


Fig 13 *The stress distribution in a neck section when the head is subjected to a force P Both tensile and compressive strains will occur (ε=strain s=superior i=inferior b=bending and p= pressure)*

allows forces to be separated from moments According to the same theories, the torque around the longitudinal axis of a beam can be determined

In accordance with these principles the strain gauges have been applied in the prosthetic neck Due to the space available, the prosthesis has been provided with four half bridges for determination of the moment and two strain gauges placed in series for determining the axial force Fig 12 shows the coupling scheme for prosthesis 2 The connection to mid point of the M bridge has been doubled The same coupling scheme applies to prosthesis 1 with the exception of gauges for M_{1x} In an outer adapting unit the strain gauges are supplemented so that five complete bridges are obtained The adapting unit is provided with a waist belt It is to be strapped around the waist so as to cause as little discomfort as possible Fig 13 shows the stress distribution in a section where the prosthetic head is subjected to force P Both tensile and compressive strains will occur in the prosthetic neck The strain measured at one point accordingly includes both tensile and compressive components These are separated by subtracting or adding the strains in two diametrical points

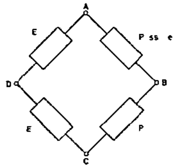


Fig 14 *Differential coupling to obtain strains from bending*

The strain caused by the bending moment is obtained by means of differential coupling as per fig 14 Thus the expression is obtained

$\varepsilon_s - \varepsilon = 2\varepsilon_b$ (s = superior, i = inferior ε_b = strain from bending) (26)

where ε_s has a positive sign and ε a negative sign
The strain caused by the axial force is obtained with coupling per fig 15
Thus the expression is obtained

$$\frac{\varepsilon_s + \varepsilon}{2} = -\varepsilon_p \ (\varepsilon_p = \text{strain from pressure}) \qquad (27)$$

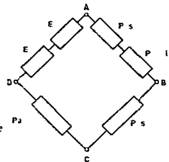


Fig 15 *Coupling to obtain strains from compressi e forces*

The strain gauges for determining M_{1x} have been placed in section 1 These gauges are connected in a complete Wheatstone bridge as shown in fig 16 and thus the expression is

$$\Sigma\varepsilon = 4 \quad \varepsilon_{tr} \ (tr = \text{torsional strain}) \qquad (28)$$

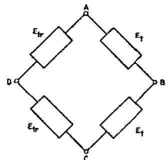


Fig 16 *Coupling to obtain torsional strains*

Temperature compensation is unnecessary for the gauges as the measuring occurs under conditions which are stable as regards temperature Difficulties can arise, however with the temperature drift for the lead wires For all moments this is compensated by the position of the gauges and the leads in the bridge For P_x the so-called Ruge-coupling has been used (fig 17) which eliminates the temperature drift of the lead wires The temperature sensitivity of the applied gauges is about 0 03 ‰ per degree C

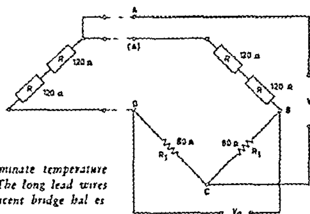


Fig 17 *Ruge coupling to eliminate temperature drift of the lead wires of P_x The long lead wires must be connected to two adjacent bridge halves*

The sensitivity of the measuring prosthesis

The amplitudes corresponding to the load shown on the oscillograph film are determined as follows

Applying for the moment sections

$$a_m = \frac{V}{} \quad g \quad \varepsilon_b \quad c \tag{29}$$

where V=bridge voltage, g=gauge factor ε_b=bending strain, c=sensitivity of galvanometer If a maximal bridge voltage of 6 volts is permissible at ε_b = 1 ‰ an amplitude of a_m = 11 3 cm is obtained

It is still assumed that no signals are received from the gauges measuring moments in section 1 which applies if the load is transmitted without friction

For the section in which the axial load P_x is measured the following applies

$$a_{p3} = \frac{V}{4} \quad \frac{R_{BD}}{R_{AC}} \quad g \quad \varepsilon_{p3} \quad c \tag{30}$$

where R_{BD}=resistance between the bridge corners BD and R_{AC}=resistance between the bridge corners AC ε_{p3}=the axial strain

As shown earlier ε_{p3}=0 165 ‰ if P=400 kp and α=60°

If a maximal bridge voltage of 12 volts is permissible, a galvanometer deflection $a_{p3} = 1\ 4$ cm is obtained

In regard to the torsion

$$a_{tr} = V \quad g \quad \varepsilon_{tr} \quad c \tag{31}$$

where

$$\varepsilon_t = \frac{M_{tx}}{E} \quad \frac{(1+\mu)}{W_{tr}} \quad \frac{d}{D_1} \tag{32}$$

where

$$\mu = 0\ 3 \text{ (Poisson s ratio)}$$

and

$$W_t = \frac{\pi (D^4_1 - d^4)}{16 \quad D_1} \tag{33}$$

With 0 9 mm section thickness (t_1) and a torque of 500 kpmm (max - moment obtained for components M_{1y} and M_{1z} when measuring with prosthesis No 1) a galvanometer deflexion $a_{tr} = 1\ 7$ cm is obtained if a max bridge voltage of 6 volts is permissible.

Calculation of calibration constants

For calibration a known resistance R_K is connected across the bridge arm BC The unbalance thereby obtained is related to the unbalance obtained by loading The following connection applies if R_K is very much greater than R

$$\frac{\Delta\ R}{R} = \frac{R}{R_K} \tag{34}$$

If the resistance change which is obtained when R_K is put in circuit, equals total resistance change in bridge when loaded the expression is obtained

$$\frac{\Delta\ R}{R} = \frac{R}{R_K} = g \quad \Sigma\varepsilon$$

thus

$$\Sigma\varepsilon = \frac{R}{g \quad R_K}$$

The following applies for the moment sections

$$\Sigma\varepsilon = 2\varepsilon_b$$

thus

$$\varepsilon_b = \frac{R}{2 \quad g \quad R_K}$$

For moment section $2\varepsilon_b$ in the foregoing expression (38) can be inserted in the following

$$LP \sin\alpha = F \quad W_{L} \quad \varepsilon_{L} \quad \frac{D}{d} \tag{39}$$

and as a result

$$M_{K} = E \quad W_{L} \quad \frac{R}{2 \quad g \quad R_K} \quad \frac{D}{d} \tag{40}$$

The moments corresponding to a number of standard values for R_K are listed in table 2

R_K	Prosthesis 1 M_K	Prosthesis 2 M_K
80 kΩ	2810 kpmm	2944 kpmm
160 kΩ	1405 kpmm	1472 kpmm
320 kΩ	703 kpmm	736 kpmm

Table 2 *The moments corresponding to known resistance R_K Section 2*

Analogous with the expression for moment section 2 the following is obtained for section 1

$$M_{1K} = E \quad W_{b1} \quad \frac{R}{2 \quad g \quad R_K} \quad \frac{D_1}{d} \tag{41}$$

giving the results presented in Table 3

R_K	Prosthesis 1 M_{1K}	Prosthesis 2 M_{1K}
160 kΩ	828 kpmm	864 kpmm
320 kΩ	414 kpmm	432 kpmm
640 kΩ	207 kpmm	216 kpmm

Table 3 *The moments corresponding to known resistance R_K Section 1*

For section 3 in which the axial force P_x is measured

$$\Sigma_E = \varepsilon_{p3} \tag{42}$$

and analogous with expression for moment sections is obtained

$$\varepsilon_{p3} = \frac{R_1}{g \quad R_K} \tag{43}$$

If formula for ε_{p3} in this expression is inserted in the expression

$$\varepsilon_{p3} = \frac{P \cos\alpha}{A_3 \quad E}$$

and as $P \cos\alpha = P_x$ (45)

this expression is obtained

$$P_x = E \quad A_3 \quad \frac{R_1}{g \quad R_K} \tag{46}$$

From this equation the values for $P_x K$ presented in Table 4 corresponding to RK are obtained

	Prosthesis 1	Prosthesis 2
RK	$P_x K$	$P_x K$
160 kΩ	304 kp	318 kp
320 kΩ	152 kp	159 kp
640 kΩ	76 kp	80 kp

Table 4 *Values of P_x corresponding to known resistances R_k*

The following applies to the torsion

$$\Sigma\varepsilon = 4\,\varepsilon_{tr} \tag{47}$$

and if

$$\Sigma\varepsilon = \frac{R}{g \quad R_K} \tag{48}$$

the expression is obtained

$$\varepsilon_t = \frac{R}{4 \quad g \quad R_k} \tag{49}$$

The expression for ε_t is inserted in equation 32, thus resulting in

$$M_{1x}k = \frac{E \quad W_t}{1+\mu} \quad \frac{R}{4 \quad g \quad R_k} \quad \frac{D_t}{d} \tag{50}$$

The moments corresponding to a number of standard values for RK have been determined and values obtained can be seen in Table 5

RK	M_1 K
160 kΩ	635 kpmm
320 kΩ	318 kpmm
640 kΩ	159 kpmm

Table 5 *The torsional moment corresponding to known resistances R_k*

The theoretical calibration constants are presented in tables 6 and 7 together with measured calibration constants

Calibration of the measuring prosthesis

The calibration method was identical for both prostheses except as regards the torsion moment as the gauges for this have only been applied in prosthesis 2

The socket of the contact was removed and the measuring prosthesis was connected to the adapting unit (fig 18) The outgoing wires of the adapting unit were connected respectively to a 5 and 6 channel balancing and calibration unit which via a switch, was connected to a signal amplifier and digital voltmeter

For moment section 2 ε_b in the foregoing expression (38) can be inserted in the following

$$LP \sin \alpha = E \quad W_t \quad \varepsilon_{12} \quad \frac{D_2}{d} \tag{39}$$

and as a result

$$M_{2K} = L \quad W_t \quad \frac{R}{2 \quad k \quad R_K} \quad \frac{D}{d} \tag{40}$$

The moments corresponding to a number of standard values for R_K are listed in table 2

R_K	Prosthesis 1 M_{2K}	Prosthesis 2 M_{2K}
80 kΩ	2810 kpmm	2944 kpmm
160 kΩ	1405 kpmm	1472 kpmm
320 kΩ	703 kpmm	736 kpmm

Table 2 *The moments corresponding to known resistance R_j Section 2*

Analogous with the expression for moment section 2 the following is obtained for section 1

$$M_{1K} = E \quad W_{b1} \quad \frac{R}{2 \quad k \quad R_K} \quad \frac{D_1}{d} \tag{41}$$

giving the results presented in Table 3

R_K	Prosthesis 1 M_{1K}	Prosthesis 2 M_{1K}
160 kΩ	828 kpmm	864 kpmm
320 kΩ	414 kpmm	432 kpmm
640 kΩ	207 kpmm	216 kpmm

Table 3 *The moments corresponding to known resistance R_k Section 1*

For section 3 in which the axial force P_x is measured

$$\Sigma\varepsilon = \varepsilon_{13} \tag{42}$$

and analogous with expression for moment sections is obtained

$$\varepsilon_{13} = \frac{R_1}{g \quad R_K} \tag{43}$$

If formula for ε_{p3} in this expression is inserted in the expression

$$\varepsilon_{p3} = \frac{P \cos \alpha}{A_3 \quad L}$$

and as $P \cos \alpha = P_x$ (45)

this expression is obtained

$$P_x = L \quad A_3 \quad \frac{R_1}{g \quad R_K} \tag{46}$$

From this equation the values for P_xK presented in Table 4 corresponding to Rx are obtained

Rk	Prosthesis 1 P_xK	Prosthesis 2 P_xk
160 kΩ	304 kp	318 kp
320 kΩ	152 kp	159 kp
640 kΩ	76 kp	80 kp

Table 4 *Values of P_x corresponding to known resistances R_k*

The following applies to the torsion

$$\Sigma\varepsilon = 4\ \varepsilon_{tr} \qquad (47)$$

and if

$$\Sigma\varepsilon = \frac{R}{g\ \ R_k} \qquad (48)$$

the expression is obtained

$$\varepsilon_{tr} = \frac{R}{4\ \ g\ \ R_K} \qquad (49)$$

The expression for ε_{tr} is inserted in equation 32 thus resulting in

$$M_{1xk} = \frac{E\ \ W_t}{1+\mu}\ \ \frac{R}{4\ \ g\ \ R_k}\ \ \frac{D_t}{d} \qquad (50)$$

The moments corresponding to a number of standard values for Rx have been determined and values obtained can be seen in Table 5

Rx	$M_{1x}K$
160 kΩ	635 kpmm
320 kΩ	318 kpmm
640 kΩ	159 kpmm

Table 5 *The torsional moment corresponding to known resistances R_k*

The theoretical calibration constants are presented in tables 6 and 7 together with measured calibration constants

Calibration of the measuring prosthesis

The calibration method was identical for both prostheses except as regards the torsion moment, as the gauges for this have only been applied in prosthesis 2

The socket of the contact was removed and the measuring prosthesis was connected to the adapting unit (fig 18) The outgoing wires of the adapting unit were connected respectively to a 5 and 6 channel balancing and calibration unit which via a switch, was connected to a signal amplifier and digital voltmeter

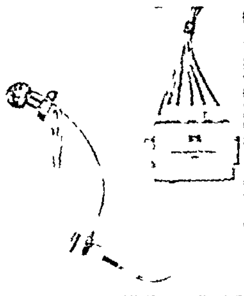


Fig 18 *The measuring prosthesis connected to the adapting unit Bofors Company Sweden*

Calibration without the prosthetic head (With adaptor)

In order to obtain as complete calibration data as possible, prosthesis 1 and 2 were calibrated before the head was mounted. For this purpose a metal cylindrical socket provided with V-shaped grooves with ball seatings was manufactured This adaptor was threaded to the neck in place of the head and the prosthesis could be loaded at defined points So that the force acting on the prosthesis would be accurately directed, suspended weights were used The load was transmitted to the prosthesis via a steel ball placed in the aforementioned ball seatings The prosthesis was secured in a holder of Resitex (fig 19)

The angles used for describing the directions of the forces are defined on page 29

The calibration of the M_x sections was performed with $\alpha=90^\circ$, $\gamma=0^\circ$ and $\beta=90^\circ$ the calibration of the M_y sections with $\gamma=90^\circ$ and $\beta=90^\circ$ The torsion moment was calibrated via a lever The gauges measuring the force P were calibrated with $\alpha=0^\circ$ and $\beta=0^\circ$

Calibration with prosthetic head

Same procedure for both prostheses except that prosthesis 2 was calibrated with and without the head glued After mounting and fixing the head, calibration was again carried out It was thus possible to get an idea as

to wether the midpoint of the moment section 1 deviated from the centre of the prosthetic head, and whether the calibration constants were changed when the head was secured

Component	M_{1z}	M_{2z}	M_{1y}	M_{y}	P_{z}
R_k (kΩ)	320	160	320	160	320
		kpmm			kp
Prosthesis 1					
Theoretical	414	1405	414	1405	152
With socket	470	1470	460	1460	171
With Ball	—	1450	—	1455	170
Definitive	470	1460	460	1460	170
Lp_y= 20 8 mm					
Lp = 20 5 mm					

Table 6 *Results of calibration prosthesis 1 Constants and distances between section 1 and 2 are given L_{py}=the lever arm of the component P_y. L_{pz}=the lever arm of the component P*

Component	M_{1z}	M_{2z}	M_{1x}	M_{1y}	M_{y}	P_{x}
R_k (kΩ)	320	160	320	320	160	320
		kpmm				kp
Prosthesis 2						
Theoretical	432	1472	318	432	1472	159
With socket	470	1520	376	460	1525	174
With Ball unglued and glued	—	1520	376	—	1520	174
Definitive	470	1520	376	460	1520	174
Lp_y= 20 9 mm						
Lp = 20 8 mm						

Table 7 *Results of calibration prosthesis 2 Constants and distances between section 1 and 2 are given L_{py}=the lever arm of the component P_y, L_{pz}=the lever arm of the component P_z*

The calibration constants and the distance between the two moment sections obtained from calibration tests are indicated in tables 6 and 7 Satisfactory agreement was obtained for the calibration constants measured in various ways Disagreement between the theoretical and measured values was largely due to the rather high ohm values of the lead wires which had been disregarded in the calculations

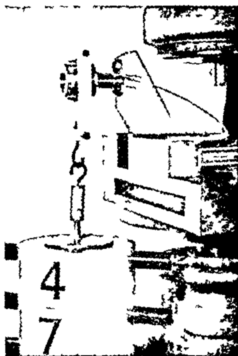


Fig 19 Calibration of the prosthes s a a cylindrical adap or Bofo s Com, any Sweden



Fig. Cont o loading of the prosthesis Bofors Company Sweden.

Control loading

To test the calibration constants obtained, the measuring prostheses were loaded under two different conditions with 40 and 80 kp, respectively Forces and angles were calculated from the recordings thus obtained These were compared with the actual loads and angles By this means an idea of the measuring accuracy was obtained The components P_x P_y and P_z were also compared

The following trigonometric connections exist

$$P_y = P \sin\beta \cos\gamma \tag{51}$$
$$P_z = P \sin\beta \sin\gamma \tag{52}$$
$$P_x = P \cos\beta \tag{53}$$

When positioning the prosthesis at given angles angles α and γ can be checked

If β is expressed in γ

$$P_y = P \cos\gamma \sqrt{\frac{1}{1+\left(\frac{\cos\gamma}{\tan\alpha}\right)^2}} \tag{54}$$

$$P_z = P \sin\gamma \sqrt{\frac{1}{1+\left(\frac{\cos\gamma}{\tan\alpha}\right)}} \tag{55}$$

$$P = P \sqrt{\frac{1}{1+\left(\frac{\tan\alpha}{\cos\gamma}\right)^2}} \tag{56}$$

Fig 20 shows how the load was transmitted to the prosthetic head. If [illegible] plane transmitting the force is correctly adjusted in the horizontal [illegible] the load is bound to act via the centre of the head

Control loadings with prosthesis 1

The prosthesis was secured in such position that $\alpha = 60°$ $\gamma = $ [illegible], and was subjected to a load of 40 kp The position was then [illegible] $\alpha = 6$[illegible] and $\gamma = 35°$ and a load of 80 kp was applied Table 8 shows [illegible] obtained

Measuring section			M_{1x}	M_{2x}	M_{1y}	M_{2y}	P	
Bridge voltage			6	6	6	6	12	Rx
P	α	γ		Vg x 500				kΩ
			mV	mV	mV	mV	mV	
			584	587	590	588	562	160
			292	294	295	294	281	320
40	60°	33°	—10	245	5	161	28	
80	60°	35°	—18	488	10	334	56	

Table 8 *Recordings of control loading prosthesis 1*

Table 9 shows a comparison between the measured and the actual values of forces and angles Corrections have been done for considering mutual interaction

	P_y kp	P_z kp	P_x kp	P kp	α	γ	β
Applied load and angles	30 2	19 7	17 4	40 0	60°	33°	64 1°
Measured uncorrected	29 1	19 4	17 0	38 9	59 8°	33 6°	64 1°
Measured *corrected*	*29 5*	*20 5*	*17 0*	*39 8*	*60 2°*	*34 8°*	*64.7°*
Applied load and angles	59 2	41 5	34 2	80 0	60°	35°	64 7°
Measured uncorrected	58 0	40 2	33 9	78 2	59 7°	34 7°	64 3°
Measured corrected	58 5	41 4	33 9	79 3	59 9°	35 3°	64 7°

Table 9 *Applied and measured forces and angles of prosthesis 1*

The percentual error for measured forces and angles is shown in table 10

		Error in %			
		P	α°	γ°	β°
P=40 kp	uncorrected	—3 0	—0 4	2 0	0 0
α=60° γ=33°	corrected	—0 5	0 4	5 5	1 0
P=80 kp	uncorrected	—1 0	—0 5	—0 9	—0.7
α=60° γ=35°	corrected	—0 9	—0 2	0 9	0 0

Table 10 *The procentual error of measured forces and angles prosthesis 1*

Control loadings with prosthesis 2

The control loadings for prosthesis 2 were carried out similarly to those for prosthesis 1 and with the same equipment The prosthesis was secured in such position that $\alpha=60^\circ$ and $\gamma=35^\circ$ In table 11 the measured and the actual values of forces and angles are presented

	P_y kp	P_z kp	P_x kp	P kp	α	γ	β
Applied load and angles	30 2	19 7	17 4	40	60°	33°	64 1°
Measured uncorrected	30 8	19 8	17 4	40 5	60 5°	32 7°	64 5°
Measured corrected	30 3	19 8	17 4	40 2	60 1°	33 1°	64 3°
Applied load and angles	52 8	34 4	30 4	70	60°	33°	64 1°
Measured uncorrected	54 0	34 4	30 5	71	60 5°	32 5°	64 5°
Measured corrected	53 2	34 6	30 5	70 5	60 2°	33°	64 4°

Table 11 *Applied and measured forces and angles of prosthesis 2*

Table 12 shows the error in % of measured forces and angles

		P	α°	γ°	β°
P=40 kp	uncorrected	1 3	0 8	—1	0 6
$\alpha=60^\circ$	corrected	0 5	0 2	0 3	0 3
$\gamma=33^\circ$					
P=70 kp	uncorrected	1 4	0 8	—1 5	0 6
$\alpha=60^\circ$	corrected	0 7	0 3	0	0 5
$\gamma=33^\circ$					

Table 12.

The moment around the x axis was tested with socket and with the prosthetic head and with different lengths of lever arms In all tests 50 kpmm corresponded to 20 mV, 100 kpmm to 40 mV, 200 kpmm to 80 mV etc

Recording of dynamic strains

Strain gauges can be used for determining dynamic strains The gauge itself will respond to strains of frequencies of more than 50,000 cps

If the prosthesis has a natural frequency close to the frequencies which are generated this might influence the recordings The natural frequency and spring constant of the prosthesis were therefore determined The natural frequency proved to be f=2 500 cps

Measuring section			M_{tx}	M_{zx}	M_{ty}	M_{zy}	P	
Bridge voltage			6	6	6	6	12	Rx
P	α	γ		vg x 500				kΩ
			mV	mV	mV	mV	mV	
			584	587	590	598	562	160
			292	294	295	294	281	320
40	60°	33°	—10	245	5	161	28	
80	60°	35°	—18	488	10	334	56	

Table 8 *Recordings of control loading prosthesis 1*

Table 9 shows a comparison between the measured and the actual values of forces and angles Corrections have been done for considering mutual interaction

	P_y kp	P_z kp	P_x kp	P kp	α	γ	β
Applied load and angles	30 2	19 7	17 4	40 0	60°	33°	64 1°
Measured uncorrected	29 1	19 4	17 0	38 9	59 8°	33 6°	64 1°
Measured corrected	29 5	20 5	17 0	39 8	60 2°	34 8°	64 7°
Applied load and angles	59 2	41 5	34.2	80 0	60°	35°	64 7°
Measured uncorrected	58 0	40 2	33 9	78 2	59 7°	34.7°	64 3°
Measured corrected	58 5	41 4	33 9	79.3	59 9°	35 3°	64 7°

Table 9 *Applied and measured forces and angles of prosthesis 1*

The percentual error for measured forces and angles is shown in table 10

		Error in %			
		P	α°	γ°	β°
P=40 kp	uncorrected	—3 0	—0 4	2 0	0 0
α=60° γ=33°	corrected	—0 5	0 4	5 5	1 0
P=80 kp	uncorrected	—1 0	—0 5	—0 9	—0 7
α=60° γ=35°	corrected	—0 9	—0 2	0 9	0 0

Table 10 *The procentual error of measured forces and angles prosthesis 1*

Barnett and Cobold (1962) tried to determine the coefficient of friction under living conditions Tests were made in a finger joint and the authors obtained a min value of 0 0075 The authors also discovered that the co efficient of friction will decrease with increasing load — a property also seen in certain types of plastic material. Under dynamic conditions it is an advantage if the coefficient of friction diminishes with increasing load, whereas under static load the opposite condition would be advantageous Hirsch (1944) demonstrated that under static load the shape of the joint surfaces are affected, which might increase the coefficient of friction
In cases where one part of a joint is replaced by a construction of metal a different coefficient of friction may be expected
In the preceding chapter it has been assumed that force P acting on the hip joint is directed through the centre of the prosthetic head If friction

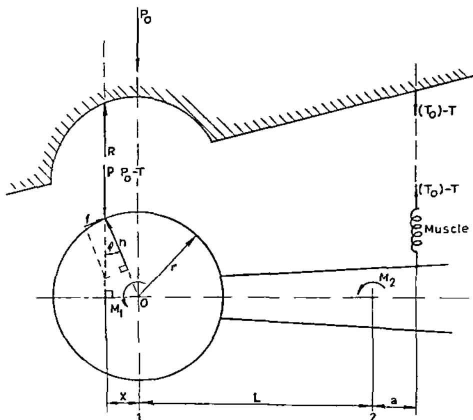


Fig 21 *Due to friction a force P_0 is displaced from the origin if the muscular force is changed by an amount T The force of reaction R will result from the normal force n and the friction force*

occurs, the combination of a normal force and frictional force can be described as if the resultant is displaced and will maintain equilibrium until the frictional force is limiting In the case of static loads such a frictional force may arise if the muscular force is increased or decreased (fig 21)

The coefficient of friction μ may be determined with the measuring prosthesis when the frictional force is limiting For the case of friction between two curved surfaces approximately the same laws apply as for an inclined plane if the contact area is not too great For the moment around the origin we have

$$M_1 = P \quad x \tag{59}$$

Fig 21 shows that

$$x = r \quad \sin \varphi \tag{60}$$

r = the radius of the prosthetic head

For small angles the sine is approximately equal to the tangent and to the angle expressed in radians As we are concerned with small angles, we can put $\sin \varphi = \tan \varphi$ Moreover, since $\tan \varphi = \frac{f}{n}$ where f is the frictional force and n the normal force acting perpendicular to f, $\tan \varphi$ = the coefficient of friction μ.

Thus, $M_1 = P \quad r \quad \mu$

but

$$M_1 = \sqrt{M^2_{1x} + M^2_{1y} + M^2_{1z}} \tag{61}$$

and the expression is obtained

$$\mu = \frac{\sqrt{M^2_{1x} + M^2_{1y} + M^2_{1z}}}{r \quad P} \tag{62}$$

This formula is valid provided that the stresses are distributed over a rather small area and the radius of friction is equivalent to the radius of the prosthetic head irrespective of the direction of the force P and distribution of the moment of friction between the axes of x, y and z However the friction radius is to some extent dependent on these factors and on the position of the prosthetic head in the acetabulum so the equation may not be exactly correct. Since the friction radius can assume values that are either greater or less than the radius of the prosthetic head the latter is an acceptable mean value of the relvant radii of friction Hence, the above expression for the coefficient of friction is probably acceptable for obtaining approximate values

The torsional moment M_{1x} need not be known to determine the magnitude and direction of P Therefore, even if M_{1x} is not measured it should be possible to obtain an approximate value for the coefficient of friction by determining μ from the resultant of M_{1z} and M_{1y} Since the coefficient of friction is to be determined when this resultant is a maximum it may be assumed that M_{1x} will be small and therefore not affect the results On the other hand, if M_{1x} is of the same magnitude as

$$\frac{M_{1z} + M_{1y}}{2} \tag{63}$$

an error is incurred which, however, will not exceed $\sqrt{\frac{3}{2}} - 1 = 20\,\%$

In prosthesis 1 no gauges were applied measuring M_{1x} but in prosthesis 2 the moment M_{1x} around the longitudinal axis of the neck part was recorded

If the contact area is too great, this method introduces an error which gives too high values of the coefficient of friction

Surgical viewpoints

Attachment

The aforedescribed measuring prosthesis shall be fixed to the femur in the same way as a conventional prosthesis This implies that the neck of the femur must have a suitable angle and that the marrow space anchorage of the prosthesis must be forced down via the neck stump into the femoral marrow space It is important that the prosthetic head and neck do not receive any hard blows when secured into the femoral marrow space In that event the measuring receptors could be damaged To facilitate insertion of the prosthesis a reamer has been manufactured Having the same dimensions as the prosthetic stem, and when inserted into the marrow space it will form a suitable bed for the prosthesis The prosthesis can thus be inserted with less force Even though the prosthesis can now be secured with light blows these blows must not be directed against the head or neck part

The angles formed by the prosthesis and femur will be decided by anatomic conditions The marrow space anchorage of the prosthesis can probably only be positioned in one way in the upper femur Due to the direction of the longitudinal axis of the proximal femur the prosthesis will form a ventral angle in the sagittal plane This angle (α in fig 1) varies slightly between different individuals According to Backman (1957) this angle is 8° with a standard deviation of ± 1 93° In evaluating the direction of force this angle must be taken into consideration

The cervico-diaphyseal angle is normally about 126° Backman (1957) has found its supplementary angle to be 54° with a standard deviation of ±5° The angle formed by the prosthetic neck and the stem is 120° As the stem follows the longitudinal axis of the proximal part of the femoral shaft, the angle formed by the prosthetic neck and the femoral shaft will be 120°, approximately

The true cervico-diaphyseal angles is, however a few degrees greater (page 35) The difference was only 1° for case 1 and 5° for case 2 The suitability of the selected neck stem angle is questionable and an angle of 125° seems to be more advantageous. In evaluating the direction of forces on the prosthetic head differences of the cervico-diaphyseal angle from the normal must be regarded

Concerning the antetorsion angle it is possible that the prosthesis will have the antetorsion angle which normally occurred in the joint previous to the operation By measuring the unoperated side approximate information of anatomic conditions in the prosthetic hip-joint is obtained, but the degree of ante-torsion may vary considerably between the left and the right side It is the only way however, of getting an idea of earlier anatomic conditions in the case in question For this reason the cervico-diaphyseal angle and the antetorsion angle for the sound hip-joint have been determined at the X ray Department of the Ekman Hospital in Gothenburg in collaboration with Billing

In collaboration with Backman at the Rontgenological Department in Lysekil the ante-torsion angle has been determined for the hip joint with the measuring prosthesis. The antetorsion angle on the prosthetic side and on the opposite side seemed to agree well Hence, no consideration has been given to eventual errors in the ante-torsion angle in determining the direction of forces acting on the prosthetic head With regard to the cervico-diaphyseal angle it has been assumed that originally this angle was of the same magnitude in the prosthetic hip as in the non operated hip

The values obtained from the two cases are presented in table 13

	Prosthesis 1		Prosthesis 2	
	opposite side	prosthetic side	opposite side	prosthetic side
Cervico diaphyseal angle	130°	120°	140°	120°
Antetorsion angle	0°	8°	38°	35°

Table 13 *Measured cervico-diaphyseal and antetorsion angles. W = 75 kp*

Sterilization

To prevent the occurrence of insulation faults, the prostheses must be sterilized in dry heat and the temperature should not exceed 125° Sterilization was therefore carried out in a Walden type autoclave with dried steam In this autoclave the relative humidity will be max 2 % and the sterilizing temperature was set at 115° C The prostheses were sterilized for a quarter of an hour After test sterilization and bacterial cultivation the prosthesis showed no growth of bacteria

Case selection

In selecting persons on whom measuring prostheses are to be inserted, the following conditions will apply

1 The patient s condition must be such that arthroplasty with a conventional prosthesis is required.
2 The patient must be willing to cooperate and also be intelligent enough to ensure satisfactory cooperation
3 Any changes in the cartilage of the acetabulum must not exist.
4 The other hip-joint must be perfectly sound and a normal walking pattern must have existed before the actual condition
5 The patient should not be too old

Case 1 was a man 51 years of age, who sustained a fracture of the head of the right femur in a motor accident With the exception of an excoriation on his face no other injuries could be detected Two loose fragments had been split from the head of the femur A rather large fragment was dislocated backwards and upwards, while a somewhat smaller fragment remained in the acetabulum Otherwise no changes could be found on the X rays The operation (Hirsch and Rydell) was performed 4 weeks after the accident with a posterior approach The gluteus maximus was split lengthwise musculus piriformis, obturator internus obturator externus and quadratus femoris were cut and the loose fragments removed At the time of the operation the cartilage in the acetabulum showed no macroscopic changes No signs of further injury to the bone structure could be found The femoral neck was adjusted to fit the prosthesis which was secured to the marrow space after a bed had first been made in the femur with a specially designed tool The prosthesis was reduced into the acetabulum The prosthesis ball fitted well in the acetabulum but its diameter was 3 mm smaller than the femoral head on the other side The joint capsule and the muscles were sutured and the cable pulled in a tunnel under the muscle fascia along the lateral dorsal part of the femur reaching more than 2/3 the length of the femur The contact cylinder was left under the fascia The skin was sutured with catgut and steel wire.

The patient was confined to bed for four weeks, during which time exercises were performed After four weeks the patient was allowed to get out of bed and then gradually to put weight on the operated leg He received exercises in walking Six months after the operation EMG tests were made giving results 'Normal EMG from gluteus medius, vastus medialis and lateralis and the adductor musles The EMG obtained from the gluteus maximus had an atypical pattern, which would agree satisfactorily with the effect of the operation ' (I Petersen) As, by this time, the patient was walking without any noticeable limp, the time appeared to be suitable for the measuring tests The patient s operated leg was then found to be 1 0 cm shorter than the sound leg The patient preferred having a 0 5 cm thick inlay in the shoe of the prosthetic side Because of the risk of infection involved by having a connection between the prosthesis in the hip joint and the external environment, the exami nations were terminated after six days Since the female contact had to be brought out by surgery, the wound might have affected the walking ability of the patient, and therefore no examinations were started until two days after this operation One exception to this was the examination made on the operation table during the awakening from the anaesthetic. The contact cylinder could be felt and by means of an incision the cylinder was brought out Fascia and skin were sutured The socket of the cylinder was removed and the first examination was carried out during his awakening from the anaesthetic The socket was then replaced and the patient was permitted to walk from the operation table to his bed This was done so as to make sure that the gauges gave the signals expected The first day the patient had some discomfort from the wound, but after 24 hours it disappeared

After the last examinations on the 6th day the teflon collar and the rein forced teflon strips which had been inserted between the leads were removed The wires were then pulled one by one towards the aforedescribed steel cylinder and then pulled out The wound healed quite normally

Case II applied to a woman 56 years of age and in good health, who fell down from a table and fractured her left femoral neck The patient was treated at home for 9 days and then sent to the hospital The X-rays showed a medial femoral neck fracture in a severe varus position and a dorsal tilt The femoral head was located practically under the neck During the operation (Hirsch and Rydell), which was performed with a technique similar to that of the preceding case, a complete avascular head was found, but the acetabulum appeared to be normal The diameter of the femoral head was exactly the same as for the prosthetic sphere

The treatment after the arthroplasty was the same as in the first case.

Seven months after the operation and when the patient walked normally EMG tests were made

From the gluteus medius and gluteus maximus on the left side no fibrillar action potentials were recorded Voluntarily, a number of potentials are activated and these are often clumsier in shape than normal and possibly of somewhat reduced quantity Furthermore, it appeared to be more difficult to find active muscle tissue than in corresponding examination on the other side The picture is not quite normal and must possibly be interpreted as the result of some mechanical muscular influence At any rate there are no signs of any neurogenic injury The EMG from the adductors of the left thigh was entirely normal like EMG from rectus femoris (I Petersén)

In this case the examinations were terminated after 8 days

The patient was confined to bed for four weeks, during which time exercises were performed After four weeks the patient was allowed to get out of bed and then gradually to put weight on the operated leg He received exercises in walking Six months after the operation EMG tests were made giving results Normal EMG from gluteus medius, vastus medialis and lateralis and the adductor musles The EMG obtained from the gluteus maximus had an atypical pattern, which would agree satisfactorily with the effect of the operation" (I Petersén) As, by this time, the patient was walking without any noticeable limp, the time appeared to be suitable for the measuring tests The patient's operated leg was then found to be 1 0 cm shorter than the sound leg The patient preferred having a 0 5 cm thick inlay in the shoe of the prosthetic side. Because of the risk of infection involved by having a connection between the prosthesis in the hip-joint and the external environment, the examinations were terminated after six days Since the female contact had to be brought out by surgery, the wound might have affected the walking ability of the patient, and therefore no examinations were started until two days after this operation One exception to this was the examination made on the operation table during the awakening from the anaesthetic. The contact cylinder could be felt and by means of an incision the cylinder was brought out. Fascia and skin were sutured The socket of the cylinder was removed and the first examination was carried out during his awakening from the anaesthetic The socket was then replaced and the patient was permitted to walk from the operation table to his bed This was done so as to make sure that the gauges gave the signals expected The first day the patient had some discomfort from the wound, but after 24 hours it disappeared

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In this case the examinations were terminated after 8 days

III Electronic walk-ways and film equipment

Forces acting on the head of the femur in walking should vary as to magnitude as well as direction in a double step Since the strain in the hip joint is great during the stance phase, and walking is perhaps the most frequent cause of strain of any appreciable magnitude in this region measuring the force on the hip joint in walking is an important part of the investigation

The force which acts on the hip joint in walking consists of one component determined by the superimposed body weight and balancing muscular forces and one component determined by the acceleration of the centre of gravity in the superimposed body mass The last component may affect the first one, which has its peak approximately in the middle of the stance-phase by making possible a balancing of the trunk without having to utilise the musculature fully It is even possible that in the stance phase the centre of gravity is shifted toward the hip-joint so that other load conditions apply than for one leg support (Rossi 1963)

In the analysis of forces acting on the hip joint in walking, it is necessary to correlate the forces to the different phases of double steps stance and swing phase, heel strike toe off, and double-support

In walking forces arise between the foot and the floor, which are generated from body weight and acceleration of the centre of gravity of the body The components of floor reactions in walking may be determined or recorded with suitable equipment generally with so-called force-plates

If recording with force-plates, one for the right foot and another for the left is carried out concomitantly with the recording of forces acting on the hip joint the latter could be correlated to a double step's different phases When evaluating the results, one must take into consideration that the vertical and horizontal force components in the hip joint as described in part II are recorded to a prosthetically fixed coordinate system while the forces which are recorded with force-plates are referred to a horizontally fixed coordinate system

The vertical force component of floor reactions during walking is dominant If this is also the case for force components acting on the hip joint in walking, which is probable the force curve which is recorded from the hip joint should have the same appearance as the course of the vertical force recorded with a force plate

Construction of the electronic floor

Floor reactions during walking are often determined by means of force plates In the chapter of references there is a brief outline on the development from pneumatic to electronic force plates With the electronic force-plates in use at present four force components are usually recorded the vertical force fore and aft shear, the lateral horizontal force and the torsional moment around a vertical axis There is one disadvantage in measuring with force plates namely that consecutive steps must be registered with a number of plates and the distance between them must be adjusted to the stride length of the person who is being tested This becomes expensive and complicated and even if the force plates are placed individually one cannot preclude that the plate might have some effect on the walk when the foot is placed on it In the present work as readings are to be used mainly to correlate the forces acting on the hip joint to various phases in a double step an electronic floor has been designed which allows measurement of consecutive steps at the same time as the fore and aft shear and the vertical component of the floor reactions are recorded

Two identical 5 metre long walking plates one for the right foot and one for the left have been constructed (fig 22) Each walking-plate consists of two U-beams joined by flat bars force transducers and stabilizing equipment The U beams with their hollow faces together form with the flat bars a framework which gives good stability and reduces the risk of deflection under load The upper U beam the plane surface of which is the footpath is 20 cm wide while the lower one is 8 cm wide The structure is made of light metal and each force plate weighs about 30 kg In

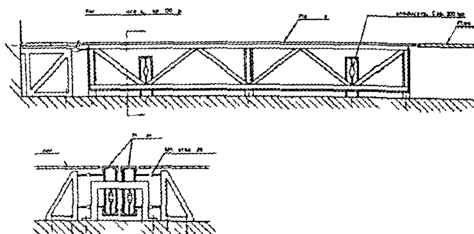


Fig 22 *An outline drawing of the electronic walk-ways*

where the force sequence begins The course of the curve is marked by two maximum points with an intermediate minimum point. The first maximum point is marked with *b* the second with *d* and the intermediate force minimum with *c* Toe-off that is to say the point where the foot loses contact with the force-plate, is marked with *e* thus *a*—*e* represents the stance-phase and *e*—*a* the swing phase. Naturally, during the swing phase no force is exerted between the foot and supporting surface. By simultaneous recording of the left and right foot, the times for double-support i e the time when both feet rest on the ground may be determined The horizontal force curve H, has a somewhat different appearance. At heel strike, there is a force peak aimed in the direction of walking This force does not occur in all the steps. After this there is a new force peak, now against the direction of walking after which comes a force peak in the direction of walking and the force returns to 0 at toe-off The point on the horizontal curve which corresponds to the heel s contact with the force-plate is marked with *f*, the first force peak with *g* the second with *h* the third with *k* and finally toe-off with *l* The point on the curve between *h* and *k*, when the force is 0, is marked with *i* The stance-phase in respect of the horizontal force curve corresponds to *f*—*l* Due to the relatively high frequency of the force *g*, this force is difficult to assess and has not been subjected to a closer analysis In measurements between different test persons, or on different occasions on the same person, curves with similar appearances are obtained In slow walking i e. in walking speeds of less than 1 m/sec., the vertical curve may look slightly different The change consists of an additional force minimum between the two peaks *b* and *d* Sometimes there is an irregularity, usually between *a* and *b* in the sequence of the curve but the nature of this has not been subjected to further analysis (fig 24)

In order to determine variations in the floor reactions in different walking

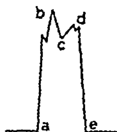


Fig 24 *Irregularities occasionally present in the recordings from the walkways*

speeds various tests have been carried out Firstly the curves for 10 men and 10 women were compared The women were tested wearing shoes with low heels medium heels and high heels Comparing the curves for the male and female test persons a slight difference could not be ruled out in the cases where the women had worn high heels The impression was that the point *d* was somewhat less in walking with high heels This was not the subject of further analysis and in this work no data were obtained for walking in high heels The criterion by which the persons tested could be considered to have a normal walk was that they had not had any illness or deformity in the lower extremities that they themselves thought they had a normal walk and that objectively, nothing noteworthy could be observed in regard to the way they walked On closer comparison between the persons tested only curves from tests where ordinary low heeled shoes had been worn were used. Before the measurements were undertaken the subjects were required to make trial walks several times in order to become relaxed In the recording a travel of 21 mm/sec was used and the time marking was carried out by means of perpendicular lines appearing on the paper at 1/10 sec intervals In order to read at time to a hundredths of a second accurately, a vernier graded in tenths of seconds and the slide graded in 9/10 was manufactured Checks have shown that readings can be made with an accuracy of ± 1/200 sec Calibration of the walking-plates took place with the aid of a calibration resistor A certain reading on the paper corresponded to a specific force By varying the bridge current the vertical force was adjusted so that the distance between each horizontal line on the paper corresponded to a load of 4 kp while for the horizontal force each line was equivalent to a force of 2 kp A static calibration was then carried out by applying a known load A reading accuracy of ± 0 2 kp was obtained for the vertical force while the accuracy for the horizontal force readings was ± 0 1 kp The force transmitters give reliable answers to very rapid dynamic sequences and the reflecting galvanometers for frequencies up to 60 cps The factor which determines the values reliability is the walking plates natural frequency This lies at about 50 cps but under load the mass increases and the frequency will probably go down still further The registered forces in all cases except the force g for the horizontal curve have a frequency which falls short of 6 cps and a sufficient margin should exist The force g as measured by the force plate has a frequency of 25 cps making the measurement values for this force unreliable

Walking speed was determined with the help of a stopwatch The test persons were permitted to use the stride length which seemed natural to them at different walking speeds

In the tests on the walking plates four successive stance phases were measured for the one leg and three for the other The first and last steps on the walking plates showed large deviations from each other The force *d* was considerably greater than *b* for the first step while for the last step the force *b* showed an excess compared to the force *d* As each end of the structure is situated at a distance of only one metre from the walls this has been construed as a sign of acceleration in regard to the first step and retardation in regard to the last In the measurements therefore, no values for the first and last steps were used

In order to find out the dissimilarities in the force sequence between two successive steps five different persons were tested on ten different occasions There was no appreciable difference as regards the time intervals and the forces for the vertical components The forces *b* and *k* for the horizontal component did however show a systematic variation The force *b* and *k* was almost always somewhat greater for the second of the analysed steps However this has been considered insignificant for the correlation of forces acting on the hip joint to forces between the foot and the floor and there has been no attempt to find an explanation for this

Ten test persons were asked to walk slowly at a medium pace and quickly, and registration was carried out with the electronic floor No measurement of the stride length was undertaken the test persons simply walked with a stride which felt natural to them The data obtained in these tests were handed over for statistical processing to Mr Carlstrom Lecturer at the Statistical Institute Gothenburg The following report was received

The statistical analysis concerns the study of the relation between walking speed and forces (force functions) versus time intervals

The analysis of the association between forces and body weight demonstrates that the relation is linear and goes through the origin of coordinates The forces have therefore been indicated in percentage of the body weight in the analyses For all y-variables (= forces/body weight, time intervals) the following has been calculated

$$y_x = a + bx$$

where x denotes walking speed

This has been carried out for both left and right observations, after which they have been compared in order to find possible differences between them If no difference could be observed the two lines have been weighted together to one line

There is a significant linear relation to walking speed in all the cases (except for g) and in no case is it possible to detect any significant difference between the right and left functions

Registration on film

If forces acting on the hip-joint in walking are required in relation to the coordinates of the body account must be taken of the position of the prosthesis in the acetabulum during e g heel strike toe-off The normal values for these angles have been determined by Barry (1952) In order to see whether the patients with the measuring prostheses moved the legs in a normal way a registration on film was carried out at the same time as the measurements with the electronic floor took place

A track for the film equipment was constructed parallel to walking plates The track consists of two steel tubes which are firmly moored to the concrete floor through supports and steel pillars The camera lighting device and a synchronizing clock are mounted on a trolley This trolley runs on wheels with roller bearings between the iron tubes and has practically vibration free movements which gives a high degree of sharpness in the film

A 16 mm Paillard film camera with wide angle lens Switar 1 1 6 f = 10 mm is used for filming The film was exposed at the rate of 64 pictures/sec The trolley with film equipment is propelled by hand at the same speed as the test person is walking (fig 25)

For projection of the film a projector which allows the feeding of one frame at a time is used To facilitate measuring the film is projected on to the back of a drawing board In the middle of the drawing board top a rectangle measuring 66 × 45 cm is removed and in its place a sheet of ground glass is inserted on to which the film is projected A tracing paper is placed over the ground glass sheet and on this paper the axes of the extremities may be drawn and angles determined

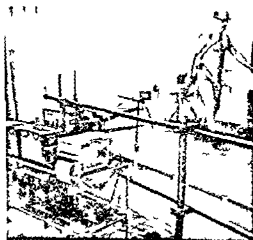


Fig 25 Case I walking on the electronic floor The film track and the film equipment can also be seen

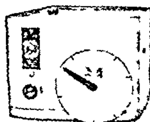


Fig 26 The synchronizing clock allowing a film frame to be connected to a certain point on the recorded curves

In the case of determining the longitudinal axes of the femur, leg and foot difficulties may arise The way to draw the axes of thigh and leg with the least faults may be debated The method which came into use does not make any claims on being exact In the present work considera tion has been taken only to the thigh s longitudinal axis in relation to the vertical line The thigh s direction was determined on the lateral side by marking the greater trochanter and the lateral femoral epicondyle and on the medial side by marking the mid point on the most proximal part of the leg which could be seen and the medial femoral epicondyle on the medial side

One obvious disadvantage which is inherent in registration on film is that from the pictures, it is not possible to decide precisely at what moment the foot touches or leaves the ground Therefore a synchronizing clock was designed (fig 26) which marks the walking plates recording paper and whose dial may be read off in the film frame In this manner a frame may be precisely synchronized to a certain point on the curves recorded by the electronic floor

Results

All of the following mean values are presented with their standard deviations

Although the subjects in which the measuring prostheses were inserted were selected with regard to age and normal anatomical conditions of the acetabulum the recordings, when done were naturally not under physio-logical conditions because a metal prosthesis never is equivalent to the parts it replaces and the surgical approach influences the function of the joint Differences of angles and dimensions between the prosthesis and the part it replaces may give changes regarding lever arms and the gait may be more or less affected

The gait of the two cases with the measuring prostheses appeared to be normal but a closer analysis showed discrepancies The force plates and simultaneous film recordings indicated that differences were present when

compared to normal people The angle v that the longitudinal axis of the thigh in the sagittal plane forms with the vertical line was measured during the heel-strike when the femur forms its greatest angle with the vertical Simultaneously the other leg, which has not yet left the ground forms its greatest angle in the sagittal plane with the vertical line and this angle called u was also determined (fig 27) When walking is abnormal these angles v and u are changed

The curve of the vertical component of floor reactions recorded by the force plates is also influenced if the gait is changed Pilot tests performed on patients with abnormal gait showed that there is a great difference in the ratio of duration of stance-phase to swing phase between the left and the right side This difference appears even in slight gait disturbances The angles v and u and the stance-swing ratio were determined for the two prostheses cases and for normal persons and the results compared The angle formed by the longitudinal axis of the femur and the vertical line in the sagittal plane was determined by means of the film frame which corresponded to heel strike for the prosthetic leg and the opposite leg, respectively This frame was projected on the ground glass of the drawing board top The longitudinal axis of the femur was ascertained by the method described previously Even if the method has some short comings with regard to accuracy of angles and axes it is useful for com parison of cases

Account has not been taken to the length of stride The subjects were told to walk in a natural way Regarding the cadence the subjects walked first slowly with a speed of about 0 8 m/sec. and then faster with about 1 2 m/sec

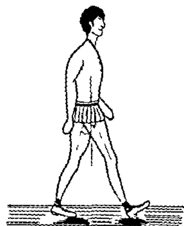


Fig 27 *At heel strike the fore leg forms an angle v with a vertical line and simultanously the hind leg forms an angle u*

To determine the accuracy with which angles can be determined with this method known angles, which were drawn were filmed and the accuracy was found to be ± 1° Greater difficulties arise when the angle is determined between the longitudinal axis of the femur and the vertical line Tests were therefore performed with legs, which were filmed bent at known angle The angles were determined with an accuracy of ±2° Berry (1952) has determined the angles *v* and *u* and found the angles to be *normally* 24° and 25° respectively in level walking In order to compare these angles to the ones obtained in this investigation the angles *v* and *u* were determined for 14 persons with a normal gait For each person six readings for every angle were made three at a cadence of about 0 8 m/sec and three of about 1 2 m/sec The individual difference did not exceed 3° The angle *v* had a mean value of 24 8°±2 1 at heel strike for the right leg and the angle *u* was for this phase 21 7±3 3 At heel strike for the left leg the angle *v* = 24 2° ± 2 5 and *u* = 20 0° ± 2 2 For the case of *prosthesis 1 the following values for angle v and u were recorded At heel* strike for the prosthetic leg *v* = 23 1° ± 1 8 and *u* = 10 0° ± 1 8 At heel strike for the opposite leg *v* = 24 3° ± 1 6 and *u* = 12 4° ± 2 8 For the case of prosthesis 2 the following values were obtained At heel strike for the prosthetic leg *v* = 21 7° ± 1 6 and *u* = 14 7° ± 2 1 and at heel strike for the opposite side *v* = 22 3° ± 0 89 and *u* = 19 3° ± 2 06 The results show that the angle *u* is less than normal in the prosthetic cases *and this is most pronounced* when *the prosthetic leg is at heel*-strike

In determination of the direction of the force acting on the prosthetic head the magnitude of the angles *v* and *u* must be taken into account as well as the fact that the longitudinal axis of proximal femur forms a dorsally opening angle with the ideal axis of the femur

An abnormal gait also gives rise to changes from the normal in the curve of the vertical component of floor reactions As mentioned earlier, pilot tests showed that even in slight disturbances of gait a difference between *the left and right side will occur in the stance swing ratio* The stance swing ratio varies with the walking speed but no difference between left and right leg exists normally

The curve of the vertical component recorded by the electronic floor showed for the case of prosthesis 1 marked differences from normal The most obvious difference was that the curves had irregularities rather frequently Normally such irregularities may occur in the curve of the vertical component *of floor reactions but not very frequently* The cause of those irregularities is obscure One explanation may be that the prosthesis had lost its grip in the femur but no indication for this appeared

on the x rays As the irregularities also were pronounced in the curves re corded by the force-plates from the unoperated side it is not likely that loosening of the prosthesis is the cause of these irregularities Another explanation may be that the diameter of the prosthetic head is 3 mm less than that of the femoral head of the opposite side, and there is a possibility of slackness in the joint At increasing speed the irregularities decreased and at fast walking they were almost absent

The difference of the stance-swing ratio between the prosthetic and the opposite side was great in case 1 at slow walking At the walking speed of 0 7 m/sec the stance-swing ratio was for the prosthetic leg 1 60 and for the opposite leg 2 57 At walking speed of 1 1 m/sec the stance swing ratio was 1 43 for the prosthetic side and 1 96 for the opposite side and with a walking speed of 1 3 m/sec the ratio was 1 47 and 1 54 respectively Differences of the ratio between two consecutive steps for the same side never exceeded 0 1 In a population of 31 normal persons the ratio between stance swing ratio on one side to stance swing ratio on the other side was 1 06 ± 0 07

For the case 2 the curve of the vertical component of floor reaction showed no irregularities and no difference between the prosthetic side and the other side appeared regarding the stance swing ratio The quotient of the stance swing ratio of the good and the prosthetic side was in 17 observations 1 04 ± 0 07

IV Intravital measurements and results

The force acting on the prosthetic head has been determined as to its magnitude and direction under static and dynamic conditions

Recordings were made for one leg support, flexion, extension, abduction and while walking In case 2 measurements were also performed while running The recordings in flexion extension and abduction were made both with and without movement

The coefficent of friction between the metal surface of the prosthetic head and the cartilage of acetabulum has also been measured

The results are valid for the prostheses only but if factors mentioned on pages 57—58 and 83—85 are considered they may give us information which could be applied to normal conditions

All of the following mean values are presented with their standard deviations

The unit of force used in this work is kilopond (kp) 1 kp is defined as the force which gives the mass 1 kilogram an acceleration of 9 80665 m/sec.^{2}

Flexion

The tests were made with the patients in the supine position A protractor with its centre situated at the top of the greater trochanter was used for determination of the amount of flexion The patients were told to lift the leg with the knee straight to a point equal to 30° 60° and 90° of flexion respectively During the tests it was difficult for the patients to keep the knee fully extended during hip flexion The force acting on the



Fig. 25 Recordings from flexion tests of case 1 when maintaining a certain degree of flexion the acting forces varied somewhat in magnitude

prosthetic head was always greater when the leg was moved The differences between dynamic and static conditions were not great except for the first 10° of flexion

Case 1

Each test was performed three times Between the tests there was an interval to allow the galvanometers to return to zero

During the tests no recordings were obtained from section 1 When the hip maintained at a certain degree of flexion the curves showed that the acting forces varied in magnitude (fig 28)

The amount of flexion in the knee joint during the tests varied about 10°—15° No attempt was made to support the knee joint by means of splints or elastic bandages The recordings obtained with prosthesis 1 can be seen in Table 14

Amount of flexion	P_y kp	P_z kp	P_x kp	P kp
30°	28 23 24	45 42 41	61 62 64	81 78 79
60°	33 29 27	47 44 41	52 51 54	78 73 73
90°	20 17 19	30 30 30	35 27 38	50 44 52
moving 0°—10°	30 33 30	42 45 49	70 74 78	87 92 97
moving 10°— 0°	37 41 40	38 38 35	68 64 66	86 84 85

	$\frac{P}{W}$	α°	γ°
30°	1 08 1 04 1 06	24 20 21	59 61 60
60°	1 03 0 98 0 97	32 30 27	55 57 57
90°	0 67 0 58 0 69	29 32 27	57 61 58
moving 0°—10°	1 16 1 23 1 29	23 25 21	55 53 59
moving 10°— 0°	1 14 1 13 1 29	29 33 31	46 42 41

Table 14 *Case 1 Flexion of the prosthetic leg W =75 kp (body weight)*

Case 2

The tests were performed in the same way as in Case 1 From ection 1 no recordings of importance occurred regarding M_{1x} The readings for M_{1y} however were not negligible These readings were negative and rather small at the beginning of flexion but increased with flexion and were great at 90° of flexion Account has further been taken of M_{1y} in evaluation of the force P No irregularities when the leg was kept flexed were found and the galvanometers returned quickly to their zero-points

As in Case 1 there were difficulties in keeping the knee extended In two tests however flexion was performed with the knee straight

The results are presented in Table 15. In Table 16 the results of the two tests, when flexion was performed with the knee fully extended, can be seen.

Amount of flexion	P_y kp	P_z kp	P_x kp	P kp
30°	21 20 20	12 13 12	42 36 36	47 43 43
60°	19 16 19	16 14 13	36 36 36	44 42 43
90°	12 11 12	16 14 14	30 30 33	36 35 38
moving 0°—10°	20 22 20	13 14 16	54 45 45	59 52 52
moving 10°— 0°	21 22 21	12 14 12	36 36 36	44 45 44

	$\frac{P}{W}$	α°	γ°
30°	1 07 0 98 0 97	27 28 28	30 34 32
60°	0 99 0 95 0 97	28 25 28	40 39 34
90°	0 82 0 79 0 86	21 21 20	55 51 49
moving 0°—10°	1 35 1 18 1 18	21 26 24	33 34 37
moving 10°— 0°	0 99 1 01 0 99	30 32 30	30 32 30

Table 15. *Case 2. Flexion of the prosthetic leg. W = 45 kp (body-weight)*

Amount of flexion	P_y kp	P_z kp	P_x kp	P kp
30°	24 23	17 17	55 58	62 64
60°	21 17	18 18	49 58	56 62
90°	11 12	14 15	24 27	30 33
moving 0°—10°	25 25	14 14	85 82	90 87
moving 10°— 0°	23 23	17 17	36 49	46 56

	$\frac{P}{W}$	α°	γ°
30°	1 40 1 46	24 22	35 36
60°	1 27 1 42	23 16	40 47
90°	0 69 0 75	25 24	52 50
moving 0°—10°	2 03 1 97	16 17	29 30
moving 10°— 0°	1 05 1 27	33 25	36 36

Table 16. *Case 2. Flexion of the hip with the knee fully extended. Prosthetic side. W = 45 kp (body-weight)*

Flexion of the opposite leg Case 1 and 2

Forces acting on the prosthetic head were also recorded in the flexion of the opposite leg The readings from M_{1y} were positive in the case of prosthesis 2 and negligible in prosthesis 1 The recordings from M_{1z} were negligible in both cases Table 17 and 18 show the results for cases 1 and 2 respectively

Amount of flexion	P_y kp	P kp	P kp	P kp
45°	16 16 22	7 6 7	25 26 38	30 31 45
90°	10 14 13	2 2 2	12 12 11	16 19 17

	$\frac{P}{W}$	α°	γ°
45°	0 40 0 41 0 59	33 31 30	24 22 19
90°	0 22 0 25 0 23	40 49 50	13 9 10

Table 17 *Case 1 Flexion of the hip Opposite side W=75 kp (body weight)*

Amount of flexion	P_y kp	P kp	P_x kp	P kp	$\frac{P}{W}$
45°	21 26 22	4 4 3	13 16 13	25 31 26	0 57 0 70 0 58
90°	13 13 15	6 5 3	12 12 12	19 18 19	0 42 0 40 0 44

Table 18 *Case 2 Flexion of the opposite leg W=45 kp (body weight)*

Discussion

The irregularities occurring in Case 1 could partly be of the same origin as the irregularities in the curves during walking

In Table 19 the mean values of angles and the ratio $\frac{P}{W}$ of the two cases in flexion on the prosthetic side are shown Although there are differences between the two cases some conclusions may be drawn The force P is always acting from the ventral side running in a dorsal direction The magnitude of the force P exceeds body weight when flexion is between 0° and 60°

Flexion of the hip gives rise to a force in the same side of about body weight if the knee is not fully extended but with a straight knee the force can reach the level of twice the body weight In the opposite side a force of about 1/2 times the body weight will act.

Amount of flexion	Case 1 $\frac{P}{W}$	α°	γ°	Case 2 $\frac{P}{W}$	α°	γ°	Case 2 straight knee $\frac{P}{W}$	α°	γ°
30°	1 06	22	60	1 02	28	32	1 43	23	35
60°	0 99	30	56	0 97	27	38	1 34	20	43
90°	0 65	29	58	0 82	21	52	0 72	25	51
moving 0°—10°	1 22	23	55	1 23	23	35	2 00	18	57
moving 10°— 0°	1 13	31	43	1 00	31	31	1 04	28	60

Table 19 *Case 1 and 2 Approximate values of $\frac{P}{W}$ and angles in flexion of the prosthetic leg W case 1 = 75 kp W case 2 = 45 kp*

Extension

The tests were performed with the subjects in prone position and with the leg extended Maximal extension was desired but in each test an additional rotation of the pelvis occurred, more pronounced in Case 2 Normally the amount of extension is 15°, but it is very difficult to perform maximal extension without rotation of the pelvis As in the prone position a small force was acting on the prosthetic head the zero lines had to be taken from a relaxed supine position The force acting in the prone position gave rise to readings from the curves of M_y and M_z Readings from M_y were positive and for M_z negative. The force P_y varied in different tests between 1 — 3 7 kp and acted in a cranial direction while the force P_z varied between 1 — 3 kp acting in a dorsal direction The force acting on the prosthetic head in a relaxed prone position might be explained by a moment developed by a force acting on the knee from the underlying surface or due to muscle forces

Case 1

Each test was repeated three times The patient was told to extend the leg fully Rotation of the pelvis occurred in every test In extension no readings were recorded from section 1 and the forces obtained can be seen in Table 20

P_y kp			P_z kp			P_x kp			P kp		
50	52	52	17	17	14	78	86	84	94	102	100

$\frac{P}{W}$			α°			γ°		
1 25	1 35	1 33	33	30	32	19	18	15

Table 20 *Case Maximal extension of the prosthetic side W=75 kp*

Case 2

The tests were performed in the same way as in case 1 In extension account had to be taken of readings from the curves of M_{1y} and M_1 The rotation of pelvis during extension was more pronounced than for case 1 The results are shown in table 21

P_y kp			P_z kp			P_x kp			P kp		
41	42	41	9	8	7	83	83	83	92	93	93

$\frac{P}{W}$			α^o			γ^o		
2 10	2 11	2 10	26	27	27	13	10	10

Table 21 *Case 2 Maximal extension of the prosthetic hip W=45 kp (body weight)*

Extension in prone position with the opposite leg

This test was only performed in Case 2 Even in this test a rotation of the pelvis occurred The results are presented in table 22

P_y kp	P kp	P_x kp	P kp	$\frac{P}{W}$	α^o	γ^o
39	17	56	70	1 56	35	24
39	18	56	70	1 56	35	25
39	19	59	73	1 62	33	27

Table 22 *Case 2 Extension of the hip Opposite side W=45 kp (body-weight)*

Discussion

Forces acting on the hip joint during extension and rotation of the pelvis are rather great In case 1 the force exceeded body-weight by about one-third and in case 2 the forces were more than twice that of the body weight.

Extension of the opposite leg gives rise to a surprisingly great force exceeding body weight by more than 50 %

Abduction

The tests were performed with the patients in supine position lying on the smooth surface of a plate This plate was graduated to facilitate the determination of the amount of abduction. The subjects were told to abduct their legs to 30° Moving of the pelvis was not allowed The maximal values recorded during abduction were determined

Forces acting on the prosthetic head when abducting the opposite leg were also determined

Case 1

In these tests the patient lying on the smooth surface was told to abduct the leg without bending the hip and knee. Table 23 shows the results obtained during abduction

Under the same conditions as for abduction of the prosthetic leg tests were performed with abduction of the opposite leg The results are seen in table 24

Abduction	P_y kp			P_z kp			P_x kp			P kp		
0°—30°	26	18	16	23	14	14	35	27	37	49	35	43

	$\frac{P}{W}$			α°			γ°		
0°—30°	0 66	0 46	0 57	37	33	23	42	39	43

Table 23 *Case 1 Abduction of the prosthetic leg W = 75 kp (body weight)*

Abduction	P_y kp			P_z kp			P_x kp			P kp		
0°—30°	12	12	12	6	6	6	13	13	12	19	19	18

	$\frac{P}{W}$			α°			γ°		
0°—30°	0 25	0 25	0 24	43	43	45	27	27	27

Table 24 *Case 1 Abduction of the opposite leg W = 75 kp (body weight)*

Case 2

As some degree of flexion during abduction in the tests of Case 1 could not be excluded the tests were this time performed in a different way The subject was lying on the same plate but had a specially made ball bearing support between the heel and the plate In this way the need of using the flexor muscles when abducting the leg was decreased The results can be seen in table 25

The abduction of the opposite leg was performed with the same technique and the forces acting on the prosthetic head were recorded The results are seen in table 26

	P_y kp			P_z kp			P_x kp			P kp		
Abduction 0°—30°	5	6	4	5	7	5	30	33	27	31	34	28

	$\frac{P}{W}$			α°			γ°		
0°—30°	0 69	0 77	0 62	8	10	8	51	51	50

Table 25 *Case 2 Abduction of the prosthetic leg W=45 kp (body weight)*

	P_y kp		P_z kp		P_x kp		P kp	
Abduction 0°—30°	4	2	2	3	6	6	8	7

	$\frac{P}{W}$		α°		γ°	
0°—30°	0 17	0 16	33	18	32	59

Table 26 *Case 2 Abduction of the opposite leg W=45 kp (body-weight)*

Discussion

The magnitude of the force P in relation to body weight is relatively equal in the two cases There is a marked difference in the values of the angle α and a small difference of the angle γ between the two cases In table 27 approximate values for the angles and the ratio $\frac{P}{W}$ of the two cases in abducting the prosthetic side are presented

Tests in adduction were excluded for technical reasons It was impossible to perform adduction without either flexing the leg or abducting the opposite leg

Case 1			Case 2		
$\frac{P}{W}$	α°	γ°	$\frac{P}{W}$	α°	γ°
0 56	31	41	0 69	9	51

Table 27 *Case 1 and 2 Approximate values of $\frac{P}{W}$ and angles in abduction of the prosthetic leg*
W case 1=75 kp W case 2=45 kp (body-weights)

Traction

To determine the effect of traction in the hip-joint the patient in case 2 was placed in the supine position and traction applied to the leg Tests were performed with the knee in flexion and extension The load was applied gradually from zero to 24 kp No force was recorded even after application of a load of 24 kp for 3 hours If a load was applied suddenly, a force was shown to be present for approximately 0 1 sec

Sitting

These tests were performed while sitting in a chair with the hips and knees flexed to 90° and with and without foot support In case 1 no forces were recorded while sitting

In case 2 small forces between 3—10 kp were present while sitting Recordings were mainly obtained from P_z P_x was always zero, P_y negative and hardly measurable

One-leg support

Standing on the prosthetic leg

The patients were told to stand on the prosthetic leg The opposite lower extremity was kept free from the floor by flexing the knee but some flexion in the hip did occur Both patients had some difficulty in maintaining this position, and in trying to maintain equilibrium they swayed to and fro This was most pronounced in case 1, who when attempting to maintain his pelvis horizontal often curved his back In case 2 the same problems arose but to a lesser degree Swaying was not as marked, and no scoliosis occurred Each time the desired position a horizontal pelvis and no curvature of the spine was maintained for a period of some seconds this was indicated on the recording paper

Case 1

Readings were made from the tests in which the patient remained in the desired position long enough for indication Even when the patient seemed to be steady oscillations of a rather high frequency occurred Readings were taken in the parts of the curve where irregularities were least pronounced

In section 1 recordings occurred for the two moments M_{1y} however had its deflections around zero in such a way that they influenced the magnitude of the force P_z very little The deflections for M_{1z} occurred in a similar way but around a line positive to the zero line In the deter

mination of the force P_y account had therefore to be taken to M_{1z}
In table 28 the magnitude and direction of the forces acting on the prosthetic head, when standing on one leg can be seen

P_y kp	P_z kp	P_x kp	P kp	$\frac{P}{W}$	α°	γ°
108	15	135	173	2 3	39	8
112	13	130	172	2 3	41	6
110	12	135	175	2 3	39	6
113	11	125	169	2 2	42	6
113	16	130	173	2 3	41	8
110	15	134	174	2 3	39	8

Table 28 *Case 1 One leg support Prosthetic leg W=75 kp (body-weight)*

Case 2

When standing on the prosthetic leg the swaying was of lower frequency and magnitude than in case 1 The curves were therefore smoother and easier to interpret

Account had to be taken of both M_{1z} and M_{1y} in section 1 in determination of the forces P_y and P , respectively M_{1z} was mainly negative but in some tests positive while M_{1y} was always positive Readings were made in the parts of the curve where the irregularities were smallest Recorded forces and angles obtained are presented in table 29

P_y kp	P_z kp	P_x kp	P kp	$\frac{P}{W}$	α°	γ°
67	10	101	120	2 7	34	9
68	11	106	120	2 8	33	9
68	12	106	125	2 8	33	10
66	13	101	120	2 7	33	11
70	13	106	125	2 7	33	11
67	13	113	129	2 9	31	11

Table 29 *Case 2 One leg support Prosthetic leg W=45 kp (body weight)*

Discussion

The force acting on the prosthetic head was on the average 2 3 times body-weight in case 1 and 2 8 times body weight in case 2 The angle α was approximately 40° and 33° angle γ 7° and 10°, respectively As can be seen from tables 28 and 29, the differences in magnitude and angles are surprisingly small between different tests in the same case There are differences however between the two cases, but regarding the directions of forces the differences are small

In case 1 irregularities in the curves produced difficulties with the readings As noted readings were taken from the smoothest parts of the curves however, because of oscillations a mean value was read

The oscillations were of lower frequency and magnitude in case 2, and smooth parts of the curves were easily found for readings

As maximal forces occurred in swaying to maintain equilibrium in what seemed to be rather static conditions, it was believed that readings might be of interest when the oscillations were at their peaks

In case 1 the force P was found to be about 190 kp or 2 5 times body-weight if the recordings were evaluated for the maximal force in one leg support In case 2 the moment M_x was also recorded and the maximal force occurred when M_x changed its direction The maximum force recorded in one leg support when standing on the prosthetic leg was about 140 kp or 3 1 times body weight One leg support is often the subject of force analysis and it might be of interest to compare the magnitude of the forces obtained by the prosthesis with theoretical values Analyses have therefore been carried out according to the laws of mechanics in a similar way to those described by Williams and Lissner (1962) This is a way to get as close as possible to the conditions existing in the operated hip joint prior to the accident Calculations were made both for the opposite and for the prosthetic side

According to Williams and Lissner (1962) fig 29 the direction of the force generated by the abductor muscles was assumed to form 71° with the horizontal plane on the normal side Assuming further that the same conditions existed on both sides the direction of the abductor pull on the prosthetic side was determined in the following way

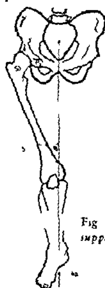


Fig 29 Determination of the force acting on the femoral bead in one leg support Fegures from case 2

Line drawings were made of the pelvis and the two femurs from x rays taken in one leg support The drawing of the prosthetic femur was placed in the opposite acetabulum with the shaft in the same direction as in one-leg support A line was drawn from the greater trochanter to the point representing the intersection between the normal direction of the abductor pull and the iliac crest. This line was assumed to represent the direction of the abductor pull of the prosthetic hip It should be understood that this method gives only approximate values

Presuming the leg to be 1/6 of the body weight the force P acting on the femoral head in case 1 was calculated on the non-operated side to be 150 kp or 2 0 times body-weight and on the prosthetic side to be 139 kp or 1 8 times body weight. The force P forms an angle with the horizontal plane on the non-operated side of 78 8° and on the prosthetic side of 76 0°

According to the differences of the cervico diaphyseal angles, the angle α between the force and the longitudinal axis of the neck is on the non operated side 38 8° and on the prosthetic side 46 0°

In case 2 the force P was found to be 105 kp on the non-operated side and 91 kp on the prosthetic side which is 2 3 and 2 0 times body weight respectively The angle formed by the force and the horizontal plane was on the non operated side 77 7° and 75 0° on the prosthetic side and the angle α 27 7° and 45 0° respectively

The differences in magnitude of the recorded forces 2 3 and 2 8 times body weight between the 2 cases are in accordance to the differences between the theoretical values The recorded forces are higher than expected from theoretical calculations

Regarding the direction of the force the theoretical calculations were only made for the frontal plane The recorded angle α between the force and the cervical axis of the prosthesis is smaller than the theoretical angle which is most pronounced in case 2 This can be due to either a more adducted femoral shaft during the tests or to muscle effects If muscle forces are the cause this might also explain the higher magnitude of the force Theoretical calculations were made with the femur in a more adducted position A slight increase of the magnitude of the force was obtained but the direction was unchanged. This is in agreement with Innman (1947) who claims that the direction of the reactive force through the head of the femur is constant and therefore independent of the position of the pelvis

Standing on the opposite leg

The patients were told to stand on the opposite leg in both cases Main

taining equilibrium was easier compared to standing on the prosthetic leg. However small oscillations occurred in case 1.

The non supporting leg can be positioned in different ways e.g. with flexion in the hip and knee joint and only with flexion in the knee joint, the hip in a neutral position or slightly in flexion, extension or abduction.

Case 1

Because of some difficulties in maintaining equilibrium in this case, the non supporting leg was kept with the knee joint in flexion and the hip was noted to move slightly involuntarily, around the neutral position.

As usual, the readings were made in smooth parts of the curves. The results can be seen in table 30.

P_y	P_x	P_z	P	$\frac{P}{W}$	α^o	γ^o
kp	kp	kp	kp			
32	15	34	49	0.65	43	26
20	14	18	30	0.40	48	36
19	10	25	33	0.44	37	28

Table 30. *Case 1. Standing on the opposite leg, the prosthetic leg bent at the knee joint but around neutral position in the hip. W=75 kp (body weight)*

Case 2

Difficulties in balancing were slight, equal to those seen in any patient. The non supporting leg was kept with the knee joint and the hip joint in 90° and 45° of flexion, respectively. The curves appeared smooth with isolated peaks. Forces and angles obtained are shown in table 31.

P_y	P_x	P_z	P	$\frac{P}{W}$	α^o	γ^o
kp	kp	kp	kp			
18	22	29	41	0.91	32	51
17	23	29	41	0.91	31	54
19	20	32	42	0.94	30	47
17	21	29	38	0.86	31	50

Table 31. *Case 2. Standing on the opposite leg, the prosthetic leg bent in hip and knee joint. W=45 kp (body weight)*

Discussion

Tests for the same subject showed differences to be rather small, but test differences of the two patients are significant. As the tests were not performed in the same way in case 1 and 2, the results are not comparable. The different behavior of the two patients in standing on the opposite side

was noticed after the evaluation of the readings, and it was then too late to perform more tests The size of angle γ shows that the force acts in a more horizontal direction in case 2 according to the coord nates of the prosthesis which is in agreement with the way the tests were performed In case 2 tests were also performed standing on the opposite leg, swinging the prosthetic leg to and fro The leg was swung from about 45° of flexion to full extension A small rotation of the pelvis in full extension could not be excluded M_{1z} and M_{1y} had to be taken into account in determining the forces P_y and P

Readings were made at the turning points a and b Point a corresponds to the instant when the leg in full extension changed direction of motion from dorsal to ventral and point b to the instant when the leg in flexion changed direction from ventral to dorsal The torsional moment around the x axis M_x changed at point a from positive to negative and at point b from negative to positive

At point a P_x and P_z were maximum while P_y increased and reached its maximum about 2/10 of a second later At point b, P_x and P_z had another maximum but P_y was at a minimum

The forces and angles obtained in these tests can be seen in table 32

	P_y kp	P_z kp	P kp	P kp	$\frac{P}{W}$	α^o	γ^o
a	28	3	27	39	0 87	45	7
b	6	20	20	29	0 65	16	68
a	23	4	27	36	0 80	40	9
b	3	19	20	28	0 62	9	81
a	26	5	22	35	0 78	50	11
b	3	21	22	31	0 69	8	81

Table 32 *Case 2 Standing on the opposite leg swinging the prosthetic leg from full extension to 45° of flexion Point a corresponds to the change of direction in full extension and b to the change of direction in maximal flexion (45°) W=45 kp (body-weight)*

Level walking

Forces acting on the prosthetic head during level walking were determined To get information on loading conditions which affect the lower extremities and the transition between the stance and swing phase recordings were made using the electronic walk ways described in part III At the same time film analyses were made Due to irregularities in the recordings (fig 30) the transition between stance- and swing phase was difficult to determine in case 1 In addition, loading conditions were not the same for the two sides All walking tests in case 1 were performed with simul-

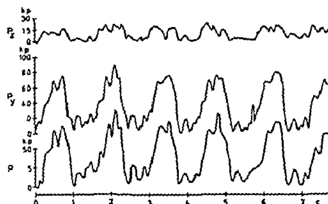


Fig 30 *The recorded force components from the hip in case 1 level walking Irregularities occurred in the recordings*

taneous recordings from the electronic walk ways In case 2 all curves were smooth and the transition between the two phases of walking was easily determined from the recordings When enough information of the difference in loading conditions between the normal and prosthetic side was obtained from the walk ways, tests were performed on a linoleum covered floor Greater walking space was thus available allowing recordings of several consecutive steps Determination of the walking speed was more accurate and a faster walking cadence was possible

In the tests on the electronic floor the first and the last steps were not included in the data The recordings on the linoleum were taken for a distance of 7 metres but the patient started walking several metres in advance of and following the test distance

Before recording any data the patients accustomed themselves to the walk ways and to the cable containing the electronic leads, which they carried over their shoulders opposite to the prosthesis

In the following, the force P and its components will be presented in relation to body weight W which was 75 kg in case 1 and 45 kg in case 2

Case 1

Level walking was performed apparently normally However recordings from the electronic floor together with film analyses revealed the differences from normal walking Though the patient had no pain there was a tendency to unload the prosthetic leg This unloading was small and the patient was not aware of it The maximum rise of the vertical force between the foot and the ground in stance phase was recorded for ten normal persons In 40 observations the mean difference between left and right side was 0 01 ± 0 06 kp/kg body weight and $t_{diff} = 0\ 86$ $p > 0\ 05$

In 48 observations on case 1 the mean difference between the normal and the prosthetic side was 0 02 ± 0 09 kp/kg body weight and $t_{d\,H} = 1\,47$ $p > 0\,05$

When considering the maximum vertical force alone the unloading of the prosthetic extremity is not great, but other signs of unloading were present. On the diagrams showing vertical force the time elapsed between heel strike point *a* and the first maximum *b* and the time between the second maximum *d* and toe-off *e* were absolutely, as well as relatively increased while the distance between the two maximum force points *b* and *d* was decreased (fig 31) These changes mean a decreased load per time unit

In addition analysis of the film studies shows that the angles between the thigh and the vertical line differ from the normal As defined on page 71—72 part III the angle *v*, (angle between the vertical line and the thigh of the leg at heel strike) is usually 25° and the angle *u* which occurs simultaneously between the vertical and the opposite thigh is usually 21° In case 1, those angles when the prosthetic leg was at heel strike, were 23° and 10° respectively At heel strike for the opposite leg *v* was 24° and *u* 12°

Recordings were made while walking at two different speeds The patient was first told to walk at his normal speed This was found to be about 0 9 m/sec His fast walking speed was about 1 3 m/sec The limited walking space prevented greater speeds

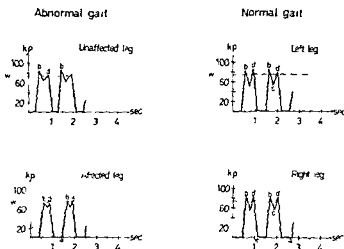


Fig 31 *The vertical force F recorded by the walk-ways is different in normal and abnormal gait indicating decreased load per time unit on the affected side*

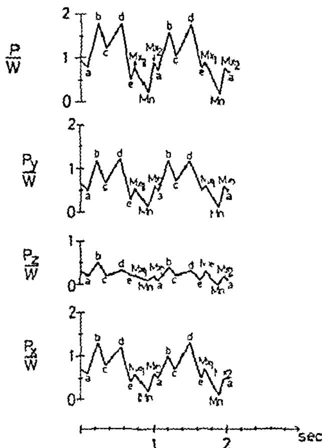


Fig 32. Level walking case 1 The force P and its components P_y, P_z and P_x in relation to body weight W. Points referred to in the text are indicated with letters W = 75 kp

Recordings from the gauges in section 1 were negligible. In most tests no displacement of the paper travel occurred. The zero drift of the gauges was of a minor degree and has been considered.

During stance phase a curve of the three recorded components from the hip was the same shape as the vertical force curve from the walk ways (fig. 32). The two maximum points and the low point in between have been designated *b*, *c* and *d*. The points corresponding to heel strike and toe off have, as in the vertical force curve, been called *a* and *e* respectively. Usually they represent low points in the recordings from the hip.

The vertical force curve from the walk ways and the P_y and P_x curves have points *b*, *c* and *d* coincident in time, while points *b* and *d* on P_z occur 0.01—0.03 sec. later.

The reason for this is not quite clear as the horizontal force occurring between the foot and the ground will have its first maximum point *b*

(see fig 23 page 65) some hundreds of a sec before *b* but the second maximum point *k* will occur about 5/100 sec later than *d* In evaluation of the force P, the small displacement of the points *b* and *d* of P_t have not been taken into account since they will have no influence of any appreciable size on the calculations

During the swing phase forces acted on the prosthetic head The curves recorded had a characteristic shape fig 32 revealing two maximum points and a low point between them The first maximum occurring shortly after point *e* is called Mx1 and the second maximum occurring just before point *a* is called Mx2 The low point is called Mn The points Mx1 and Mx2 occur simultaneously in all curves, but the point Mn occurs for P 0 02—0 05 sec earlier

The irregularities occurring in all recordings from the hip joint are difficult to explain and have not been included in the data One explanation could be an improper fit of the prosthetic head in the acetabulum The prosthetic head is 3 mm smaller than the femoral head of the other side Other possibilities are that the irregularities are due to muscular effects or to small movements of the stem in the femur However the irregularities diminish with increased walking speed

Evaluation of the curves was performed in one of two ways Some were evaluated by use of a vernier scale or by graded transparent plate Others were done mechanically by automated electronic equipment Analysis of the curves by the first method included only those points *a b c d e* Mx1, Mn and Mx2 Analysis by the electronic method permitted evaluation of points on the curves separated by an interval of 0 04 sec

The points *a* and *e* representing heel strike and toe off are usually low points but not zero points in the curves of the hip joint Point *e* was negative in only one of thirty six observations this was for P_y Mn was negative five times for P four times for P_y The negative recordings were small, under 5 kp except on one occasion when P_y was —9 6 kp

In table 33 the components and the force P are presented in relation to body weight at a walking speed of 0 9 m/sec and in table 34 the same data are presented at a walking-speed of 1 3 m/sec The number of observations are 21 and 12 respectively When the acting forces are great the variation is rather small The measuring accuracy is low when the recorded figures are small, and this may explain the great variation at those points where the forces are small

The direction of the forces at the points *b c d* M_{x1} and M_{x2} can be seen in tables 35 and 36 The point of application of the force is suprisingly constant The head of the prosthesis mainly is subjected to a force coming from above ventrally and medially

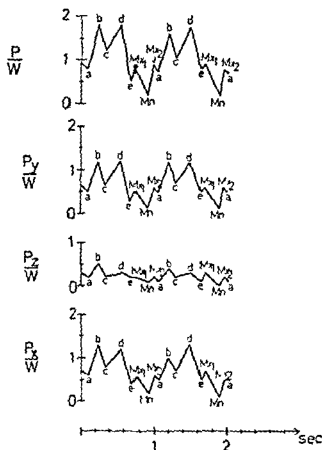


Fig 32 Level walking case 1 The force P and its components P_y, P_z and P_x in relation to body weight W Points referred to in the text are indicated with letters W=75 kp

Recordings from the gauges in section 1 were negligible In most tests no displacement of the paper travel occurred The zero-drift of the gauges was of a minor degree and has been considered

During stance-phase a curve of the three recorded components from the hip was the same shape as the vertical force curve from the walk ways (fig 32) The two maximum points and the low point in between have been designated *b* *c* and *d* The points corresponding to heel strike and toe off have as in the vertical force curve, been called *a* and *e* respectively Usually they represent low points in the recordings from the hip

The vertical force curve from the walk ways and the P_y and P_x curves have points *b* *c* and *d* coincident in time, while points *b* and *d* on P_z occur 0 01—0 03 sec later

The reason for this is not quite clear as the horizontal force occurring between the foot and the ground will have its first maximum point *b*

Because of the low accuracy in recording small forces, the direction of the forces have not been determined at such points The patient was also tested while walking with a cane When walking out doors he usually used a cane as a security against falling He was told to use the cane *in the same way while walking on the walk ways and recordings were* made When using the cane in the opposite hand there was a considerable unloading of the prosthetic leg When using the cane in the hand of the prosthetic side unloading of the opposite extremity was recorded the patient was not aware of any unloading regardless on what side he used the cane

Case 2

Level walking was performed in an apparently normal manner Recordings from the electronic floor and film analyses revealed only slight differences from the normal The stance/swing ratio between the opposite and prosthetic side was normal regardless of the walking speed There were no signs of unloading of the prosthetic leg but the maximum rise of the vertical force between the foot and the ground was recorded for both sides and in 29 observations the mean difference was $0\ 02 \pm 0\ 09$ kp/kg body weight and $t_{diff} = 1\ 27$ $p > 0\ 05$ between the normal and the prosthetic side

The angles formed by the longitudinal axes of the thighs and the vertical line differed less from the normal than in case 1 In case 2 when the prosthetic leg was at heel strike the angle v was 22° and angle u 15° and when the opposite leg was at heel strike the angles were 22° and 19° respectively The angle u was slightly less than normal when the prosthetic leg was at heel strike (part III page 72)

Recordings were made at different walking speeds The most convenient speed was 1 1 m/sec but when asked she increased the speed up to 1 6 m/sec Further increase of speed was only obtained while running The different tests could be grouped in two parts one group of walking tests at a speed of about 1 1 m/sec and another group at about 1 4 m/sec The results are therefore presented in mean values and standard deviations from these two groups

Recordings from the gauges in section 1 have always been taken into account and all readings were made optically No zero drift occurred The shape of the curves (fig 33) differed somewhat from those of case 1 During the stance-phase two maximum points and a low point in between occurred in accordance with the curve F and recordings from case 1 The points corresponding to Mx_2 in the swingphase and to point a at heel strike were represented by a plateau of the curves The points

	$\frac{P_y}{W}$	$\frac{P_z}{W}$	$\frac{P_x}{W}$	$\frac{P}{W}$
a	0 29±0 10	0 08±0 05	0 32±0 16	0 45±0 16
b	0 97±0 06	0 31±0 06	1 11±0 11	1 51±0 13
c	0 81±0 05	0 15±0 07	0 96±0 11	1 24±0 10
d	1 06±0 09	0 26±0 09	1 15±0 11	1 59±0 11
e	0 12±0 09	0 04±0 04	0 15±0 09	0 20±0 11
Mxi	0 33±0 07	0 10±0 04	0 35±0 11	0 50±0 12
Mn	0 07±0 06	0 01±0 02	0 14±0 09	0 17±0 09
Mx	0 37±0 10	0 11±0 05	0 43±0 12	0 59±0 13

Table 33 Case *I* *Level walking at 0 9 m/sec W=75 kp (body weight), n=21*

	$\frac{P_y}{W}$	$\frac{P}{W}$	$\frac{P_x}{W}$	$\frac{P}{W}$
a	0 55±0 26	0 15±0 09	0 58±0 26	0 84±0 34
b	1 19±0 17	0 48±0 09	1 29±0 22	1 80±0 29
c	0 77±0 11	0 16±0 09	0 82±0 13	1 15±0 14
d	1 20±0 15	0 34±0 06	1 24±0 13	1 76±0 18
e	0 30±0 20	0 15±0 10	0 37±0 15	0 51±0 24
Mxi	0 54±0 22	0 24±0 09	0 59±0 17	0 84±0 28
Mn	0 11±0 10	0 05±0 05	0 17±0 10	0 23±0 12
Mx	0 57±0 12	0 19±0 05	0 55±0 15	0 85±0 14

Table 34 Case *I* *Level walking at 1 3 m/sec W=75 kp (body weight) n=12*

	α°	γ°
b	41±2	18±3
c	42±3	11±5
d	43±3	13±3
Mxi	44±8	17±5
Mx	42±9	17±6

Table 35 *Case I Level walking at 0.9 m/sec n=21*

	α°	γ°
b	45± 7	22±4
c	44± 9	11±6
d	44± 6	16±3
Mxi	42±10	25±9
Mx	45±10	19±6

Table 36 *Case I Level walking at 1 3 m/sec n=12*

The vertical force curve F from the walk ways and the P_y and P_x curves have points *b* *c* and *d* coincident in time while points *b* and *d* on P_x as in case 1 occurred 0 01—0 03 sec. later

In table 37 the components and the force P are presented in relation to body-weight at a walking speed of 1 1 m/sec and in table 38 the same data are presented at a walking speed of 1 4 m/sec The number of observations are 24 and 18 respectively The direction of the forces at points *b* *c* *d* and Mx₂ is seen in tables 39 and 40

	$\frac{P_y}{W}$	$\frac{P_x}{W}$	$\frac{P}{W}$	$\frac{P}{W}$
b	1 52±0 08	0 50±0 04	2 49±0 15	2 95±0 16
c	0 94±0 21	0 06±0 04	1 54±0 11	1 86±0 12
d	1 35±0 08	0 26±0 06	1 74±0 13	2 23±0 12
Mx.	0 64±0 09	0 12±0 03	1 02±0 12	1 21±0 13

Table 37 *Case 2 Level walking at 1 1 m/sec W=45 kp (body-weight) n=24*

	$\frac{P_y}{W}$	$\frac{P}{W}$	$\frac{P}{W}$	$\frac{P}{W}$
b	1 71±0 17	0 52±0 09	2 74±0 28	3 27±0 32
c	1 09±0 10	0 04±0 06	1 60±0 20	1 94±0 21
d	1 56±0 12	0 32±0 06	1 98±0 17	2 55±0 19
Mx	0 72±0 12	0 10±0 03	0 88±0 15	1 15±0 18

Table 38 *Case 2 Level walking at 1 4 m/sec W=45 kp (body-weight) n=18*

	α°	γ°
b	31±1	18±1
c	34±2	3±3
d	38±2	11±3
Mx₂	34±4	10±2

Table 39 *Case 2 Level walking at 1 1 m/sec n=24*

	α°	γ°
b	32±1	17±3
c	34±2	2±3
d	38±2	12±2
Mx₂	39±3	8±3

Table 40 *Case 2 Level walking at 1 4 m/sec n=12*

The point of application of the force is rather constant and differs little from case 1 The head of the prosthesis is subjected to a force directed against a rather small area of the medial upper ventral surface

Stair-walking

The force acting on the prosthetic head while walking up- and downstairs was determined The stairs were made of stone and each step was 15 cm high In case 1 the stairs were 270 cm long and in case 2 the stairs were 360 cm long In the analyses, recordings from the first step and the last step have not been included

Before recording any data the patients climbed the stairs several times to become accustomed to them During the tests the cable containing the leads was carried over the shoulder opposite to the prosthesis

No recordings with force-plates were made This meant that the transition between the stance- and swing phase could not be determined

In the following the force P and its components are presented in relation to the bodyweight W In case 1, W equals 75 kg and in case 2, 45 kg

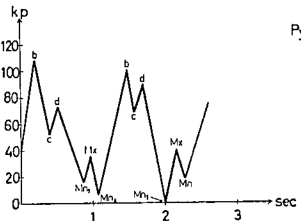
Walking upstairs Case 1

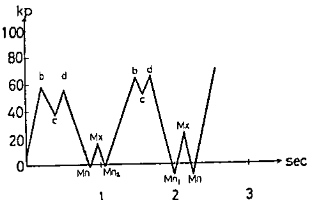
In case 1 stair-walking was performed with ease. Because he always limped on the first two steps the recordings started two steps below the measured distance In all tests the walking speed was 0 6 m/sec If he altered this speed the gait was slightly affected

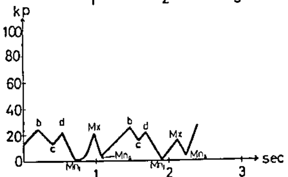
Recordings from section 1 were negative In the readings consideration had to be taken of a minor zero drift and displacement in the travel of the recording paper The zero-drift was most obvious regarding P_y The zero line was therefore determined individually for each step

The shape of the recorded curves in the stance-phase was similar to that for level walking Though the exact transition between the stance- and swing phase could not be determined the maximum and minimum forces of the two phases could be separated

As in level walking two maximum points *b* and *d* and a minimum point *c* which occurred between *b* and *d*, were present in the stance phase (fig 34) In walking upstairs however the *b*- *c*- *d* part of the curve was narrower and the force representing the point *b* was always considerably greater than at point *d* This was most pronounced for the component P_z Compared to level walking the swing phase revealed a different curve In walking upstairs two minimum points Mn_1 and Mn and a single maximum point Mx occurred during the swing phase (fig 34) Points Mn_1 Mn and Mx were coincident on the time axis for P_y and P_x For P_z Mn_1







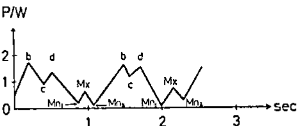


Fig 34 *Walking upstairs case 1 The components are presented in kp and the force P in relation to body weight W Points refered to in the text are indicated with letters W=75 kp*

The point of application of the force is rather constant and differs little from case 1. The head of the prosthesis is subjected to a force directed against a rather small area of the medial, upper ventral surface.

Stair-walking

The force acting on the prosthetic head while walking up- and downstairs was determined. The stairs were made of stone and each step was 15 cm high. In case 1 the stairs were 270 cm long and in case 2 the stairs were 360 cm long. In the analyses recordings from the first step and the last step have not been included.

Before recording any data the patients climbed the stairs several times to become accustomed to them. During the tests the cable containing the leads was carried over the shoulder opposite to the prosthesis.

No recordings with force-plates were made. This meant that the transition between the stance and swing phase could not be determined.

In the following the force P and its components are presented in relation to the bodyweight W. In case 1, W equals 75 kg and in case 2 45 kg.

Walking upstairs Case 1

In case 1 stair walking was performed with ease. Because he always limped on the first two steps the recordings started two steps below the measured distance. In all tests the walking speed was 0.6 m/sec. If he altered this speed the gait was slightly affected.

Recordings from section 1 were negative. In the readings consideration had to be taken of a minor zero drift and displacement in the travel of the recording paper. The zero drift was most obvious regarding P_y. The zero line was therefore determined individually for each step.

The shape of the recorded curves in the stance-phase was similar to that for level walking. Though the exact transition between the stance- and swing phase could not be determined the maximum and minimum forces of the two phases could be separated.

As in level walking two maximum points *b* and *d* and a minimum point *c* which occurred between *b* and *d* were present in the stance-phase (fig 34). In walking upstairs however the *b c- d* part of the curve was narrower and the force representing the point *b* was always considerably greater than at point *d*. This was most pronounced for the component P_x. Compared to level walking the swing phase revealed a different curve. In walking upstairs two minimum points Mn_1 and Mn and a single maximum point Mx occurred during the swing phase (fig 34). Points Mn_1, Mn and Mx were coincident on the time axis for P_y and P_x. For P, Mn_1

as in case 1 When the patient was told to walk faster her walking speed was 0 9 m/sec but during the stance-phase the curves developed a different shape. As in running the points *b*, *c* and *d* were replaced by a single peak *bd* (Fig 35)

The readings were easily recorded as no zero-drift or displacement of the recording paper occurred As in case 1 the exact transition between the stance phase and the swing phase could not be determined In the tests when the walking speed was slow and both points *b* and *d* were distinct the force acting at point *b* was considerably greater than at the point *d* The force acting at point *b* was of about the same magnitude as the force acting at point *bd* at the higher walking speed and therefore point b has been analysed together with point *bd*

In the swing phase the same displacement of point Mn_1 for the force P_x as in case 1 occurred P_z showed at Mn a steeper slope and P_z was sometimes negative P_y and P_z were maximum at point Mx but for P_x it was only a point of inflection or had a less steep slope As P_x was the greatest component of the force P it did not always have a maximum at point Mx

Table 43 shows the forces acting on the prosthetic head and table 44 shows the direction of the forces at the points *bd* and Mx As in case 1 the direction of the force at the points Mn_1 and Mn_2 cannot be determined with accuracy No negative values were recorded for P_y but P_z was negative in six of fourteen steps at point Mn The negative forces were small and did not exceed 3 kp The head of the prosthesis was thus occasionally subjected to a small force momentarily applied coming dorsally from above

	$\frac{P_y}{W}$	$\frac{P}{W}$	$\frac{P_x}{W}$	$\frac{P}{W}$
bd	1 72±0 16	0 44±0 04	2 87±0 19	3 38±0 18
Mn_1	0 23±0 07	0 20±0 05	0 36±0 12	0 48±0 12
Mx	0 26±0 07	0 20±0 05	0 35±0 12	0 46±0 16
Mn_2	0 12±0 06	0 01±0 05	0 10±0 11	0 20±0 09

Table 43 *Case 2 Walking upstairs W = body weight 45 kp n = 14*

	α^o	γ^o
bd	31±3	15±2
Mx	37±9	37±5

Table 44 *Case 2 Walking upstairs n = 14*

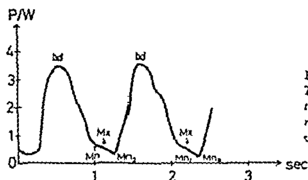


Fig 35 Walking upstairs case 2 The force P is presented in relation to body weight W and the points refered to in the text are indicated with letters W=45 kp

Walking downstairs Case 1

The patient walked downstairs apparently normally, but subjectively he felt insecure compared to walking upstairs The walking speed was constant in all tests and any attempt to alter it affected the gait

The recordings from section 1 were negligible A slight zero drift and displacement in the travel of the recording paper occurred as while walking upstairs and has been taken into account The shape of the curves were the same walking downstairs as in walking upstairs both in the swing phase and the stance-phase. In the stance-phase however there was a difference in magnitude as the force at point *d* always was greater than at point *b* (fig 36) The point Mn_2 for the force P_z appeared 1/10 sec earlier than for P_y and P_x At the points Mn_1 and Mn the force P_y was always negative and small The point Mx was always maximum for all components

In table 45 the forces acting on the prosthetic head are presented In table 46 the direction of the forces at the points *b c*,*d* and Mx are shown Because of the low degree of accuracy in measuring small forces, the directions of forces at the points Mn_1 and Mn_2 are not presented When the force P_y is negative at these points, the head is subjected to a force coming from below and ventrally

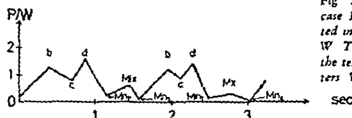


Fig 36 Walking downstairs case 1 The force P is presented in relation to body weight W The points refered to in the text are indicated with letters W=75 kp

	$\frac{P_y}{W}$	$\frac{P_x}{W}$	$\frac{P_z}{W}$	$\frac{P}{W}$
b	0 80±0 05	0 27±0 07	0 96±0 09	1 29±0 11
c	0 60±0 11	0 17±0 08	0 71±0 18	0 95±0 19
d	0 95±0 09	0 39±0 09	1 21±0 18	1 59±0 18
Mn₁	—0 12±0 05	0 12±0 04	0 08±0 07	0 20±0 02
Mx	0 07±0 06	0 22±0 09	0 32±0 12	0 40±0 13
Mn	—0 04±0 02	0 11±0 05	0 12±0 08	0 17±0 08

Table 45 *Case 1 Walking downstairs W=body-weight 75 kp n=8*

	α^o	γ^o
b	40±2	19±5
c	40±6	16±6
d	38±3	23±5
Mx	17±9	68±8

Table 46 *Case 1 Walking downstairs In one recording at point Mx the angle α was —22° and angle γ was —50° These values are not included n=8*

Walking downstairs Case 2

The patient walked apparently normally and was able to vary her walking speed The shape of the curves was the same as in walking down stairs case 1 The force acting at point *d* was considerably greater than at point *b* (fig 37)

The readings from section 1 have been taken into account in the deter mination of the forces No zero-drift or displacement of the recording paper occurred and no negative values were recorded

In table 47 the recorded forces are shown and in table 48 the direction of the forces at points *b* *c* *d* and Mx are shown In all tests the head of the prosthesis was subjected to a force coming from above ventrally and medially

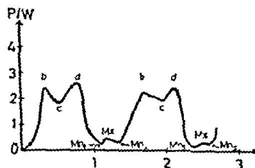


Fig 37 *Walking downstairs case 2 The force P is presented in relation to body weight W The points refered to in the text are indicated with letters W=45 kp*

	$\frac{P_y}{W}$	$\frac{P_z}{W}$	$\frac{P_x}{W}$	$\frac{P}{W}$
b	1 59±0 25	0 47±0 10	2 21±0 35	2 77±0 41
c	1 32±0 15	0 33±0 06	1 79±0 33	2 25±0 59
d	1 75±0 11	0 43±0 07	2 17±0 34	2 83±0 31
Mn_1	0 12±0 08	0 04±0 03	0 11±0 07	0 18±0 06
Mx	0 29±0 16	0 08±0 04	0 26±0 14	0 42±0 17
Mn	0 21±0 16	0 05±0 04	0 17±0 13	0 30±0 16

Table 47 *Case 2 Walking downstairs W=body weight 45 kp n=12*

	α^0	γ^0
b	36± 3	17± 3
c	37± 4	14± 2
d	39± 4	14± 2
Mx	47±20	21±17

Table 48 *Case 2 Walking downstairs n=12*

Discussion

While walking up and downstairs, the curves of the force components in the stance phase have a shape similar to those in level walking and running *In the swing phase, however the shape of the curve differed in* that it had low points with a maximum in between

While walking upstairs the force acting at point *b* was considerably greater than at point *d* and in case 2 when the speed was increased the points *b* *c* and *d* fused to one point *bd* as occurred while running

While walking downstairs the point *d* in the stance phase was considerably greater than point *b*

In all tests the point Mn_1 in the swing phase appeared 1/10 sec earlier for P_z than for the other two components In case 1 the force P_y frequently was negative which could be due to errors in the readings When negative the forces were always small *In case 2, while walking upstairs* P_z was negative occasionally at point Mn Point Mx was always a maximum point for the components P_y and P_z but in walking upstairs for P_x it is a point where the curve changes its slope Because P_x usually is the main component of the force P Mx does not always correspond to a maximum point on the force diagram of P

When the force was great as at points *b* *c* and *d* and sometimes at point Mx the direction of force varied slightly and the prosthetic head was loaded in the usual area (superiorly ventrally and medially) At point

Mx the direction of the force becomes more horizontal and has greater variation

The shape of the curves and the direction of the forces were in agreement in the two cases The magnitude of the forces was however different The force on the prosthetic head relative to body weight was greater in the stance-phase of case 2 Theoretical calculations indicate a higher load to occur in the stance phase of case 2 The test results show the load difference to be greater than those calculations indicate

Running

Running causes the force acting on the femoral head to be of high magnitude The following information is on measurements performed while running

Case 1 was afraid to run therefore no tests were performed

Case 2 was able to run easily The patient stated she had not run for the last 30 years but was able to do so without difficulty When she became accustomed to running the recordings were started

The running tests were first performed on the walk-ways to determine the transition between the stance- and swing phase. Then the tests were repeated on a linoleum covered floor of greater space The recordings on the linoleum were taken for a distance of 7 metres but the patient started to run several metres in advance of and continued to run after completing the test distance

Running was performed at a speed of about 2 0 m/sec and could be easily increased to 3 0 m/sec Increasing the speed beyond this was deemed inadvisable

No significant differences in the magnitude of forces were obtained at different speeds Analyses have been made for 19 steps The original curves have been analyzed in a computer which gives the forces and angles numerically and graphically (fig 38)

Evaluation of the curves has considered the recordings of section 1

The vertical force F recorded by the walk-ways measuring devices has only one peak in running here called *bd* The forces recorded from the hip device has the same peak *bd* in the stance-phase. This peak occurred simultaneously for F P_x and P_y For P_z however the point *bd* occurred 0 02—0 04 sec later All readings for point *bd* were made when P_x and P_y reached this peak which means that the values for P_z were taken just before its peak The difference thus occurring is negligible except for the angle γ which at point *bd* of P_z would be significantly higher

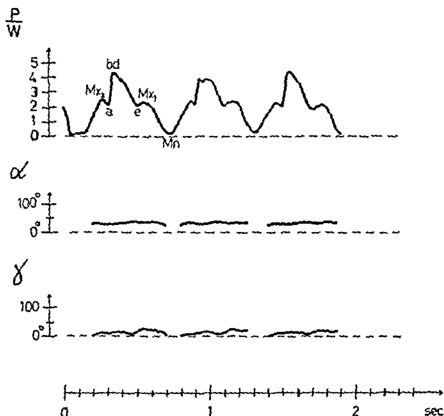


Fig 38 *Running case 2 The force P is presented in relation to body weight W The variation of the angles α and γ in the stance phase is indicated W=45 kp*

As in level walking two maximum points Mx_1 and Mx and a low point between the two peaks occurred in the swing phase Mx_1 and Mx were however of much higher magnitude than in level walking At point Mn the readings for P_x were always negative and for P_z and P_y positive Recorded values at the points *a* and *e* were also of high magnitude In Tables 49 and 50 forces and angles obtained are presented At point Mn the direction of the force is not certain because the acting forces are small and the accuracy of recording low The mean value of α was 15° and γ —66° at Mn but varied greatly

The angle γ is small, about 10° at point Mx and *a*, and then increased throughout the stance phase to reach its greatest value 25° at Mx_1 This fact is contrary to that which was expected

	$\frac{P_y}{W}$	$\frac{P_x}{W}$	$\frac{P_x}{W}$	$\frac{P}{W}$
a	1 21±0 13	0 21±0 03	1 92±0 25	2 28±0 27
bd	2 26±0 17	0 59±0 09	3 65±0 29	4 33±0 32
e	1 28±0 22	0 42±0 08	1 81±0 34	2 26±0 39
Mx1	1 28±0 15	0 60±0 12	2 01±0 39	2 49±0 44
Mn	0 04±0 04	—0 09±0 04	0 15±0 11	0 20±0 08
Mx	1 30±0 11	0 23±0 03	2 09±0 20	2 47±0 22

Table 49 *Case 2 Running at about 2 5 m/sec W=45 kp n=19*

	α°	γ°
a	32±3	10±1
bd	32±2	15±2
e	35±4	19±5
Mx1	33±4	25±3
Mx	32±2	10±1

Table 50 *Case 2 Running at about 2 5 m/sec W=45 kp n=19*

Coefficient of friction

The measuring prosthesis enables us to get an approximate value of the coefficient of friction The theories regarding this are presented in part II page 54—57 Determination of this quantity is dependent on the size of the contact area and it will be accurate only if the contact area is not too great If the contact area is large the recorded values will be too high The diameter of the femoral head is normally less than that of acetabulum and in case 1 this differential is greater since the prosthetic head is about 3 mm smaller than the original head In case 2 the diameter of the prosthetic head is about the same as that of the original head The contact area is therefore probably greater in case 2

Case 1

As described in part III page 57 the torque M_x was not recorded This introduces an error but the error does not exceed 20 % If M_x is smaller than M_{1y} and M_{1z} as it usually was in case 2 the error is less

The coefficient of friction was determined under dynamic conditions while walking and under static conditions while standing on one leg and keeping the leg flexed against a resistance

While walking, the *coefficient of friction* changed after about 25 metres The *patient* at the *same time* complained of fatigue but not pain in the hip The coefficient of friction returned to its usual value *after resting* The dynamic coefficient of friction was found to be 0 021 ± 0 001 in 12 tests and after walking about 25 metres 0 033±0 003

The *static* coefficient of friction was markedly increased Standing on one leg gave 0 115±0 016 after 30 readings and in the *supine position* when flexing and abducting the leg the *coefficient* was 0 102±0 018

The tests *performed* under *static* conditions may not always produce maximum friction so that the real values would be somewhat higher than the mean value

Case 2

In this case M_x was recorded as well as M_{1y} and M_{1z}

The coefficient of friction could *not* be determined under static conditions as *no movements occurred* From the gauges of section 1 only a single *steady* deflection occurred under *load* below the frictional forces

While walking a maximal moment about *the y-axis* developed *in* the middle of *the* stance-phase and *ended in* the beginning of the swing-phase This moment *is probably* generated by catching *of* the prosthetic head against the ventral ligaments of the joint and is *not* due to *friction*

The coefficient of friction in this case was *determined from point b in* the stance phase and from Mx *in the swing phase*

The value obtained *in* 36 *tests* was 0 042 ± 0 013 The inherent error in determining the coefficient of friction is greater in case 2 than in case 1 since the head acetabulum diameter ratio in case 2 gives a greater contact surface

V Recapitulation and discussion

Analyses of forces acting on bone, stress and strain in bone under load and determination of physical properties of bone have been made by several anatomists and orthopaedic surgeons However, theoretical calcu lations are complicated as bone is a heterogenous material and of complex geometric shape Much of the force is due to muscular activity and it is difficult to determine quantitatively Analyses even with small demands upon accuracy, can only be done under idealized conditions
Actual measurements of forces with their stresses and strains will provide more accurate results and enable theory to be confirmed or altered Specimen measurements have informed us of stress concentrations and fracture mechanisms Specimen testing is limited since the force vectors acting under vital conditions are unknown The only possible way to get information regarding the magnitude and direction of physiological forces is to record them under vital conditions
At present it is impossible to record forces under pure physiological con ditions because introduction of the measuring device will disturb the normal state This must be taken into consideration when evaluating the results of such recordings

The measuring prosthesis

The purpose of this work was to measure forces acting on a prosthetic head of femur in the active patient At the start it was clear that quantitative measurements on living bone would be impossible with the techniques available today This has been done on specimens (Hirsch and Frankel 1960 1961) The proximal part of the femur is quite often replaced by a metal prosthesis and since metal is a highly suitable material for support of a strain gauge, it was thought that placing strain gauges into a prosthetic neck would provide an easy way to measure forces acting on the hip Strain gauge placement on the neck of a prosthesis permits that prosthesis to act as a force transducer Three orthogonal force components are recorded from this device which permits the resultant force to be computed A femoral endo prosthesis acting as a three dimensional force transducer while main taining its clinical purpose was proposed
From an electronic viewpoint the construction of a measuring prosthesis was not difficult The neckpart became the transducer and the strain gauges were applied as in a six component strain gauge balance

Strain gauges are sensitive to moisture and temperature changes so they were placed inside the neck where they were protected from body fluids and where the temperature would remain constant

Problems which arose were purely of technical origin The neck of the prosthesis had to be small and the area available for the strain gauges was limited If the measurements were to be accurate the dimensions of the prosthesis had to be exact The material requirements for the prosthesis were easy machinability with adequate strength to permit small dimensions The prosthetic shape had to fit anatomical structures and the material be without toxic effect

Design of the prosthesis had to account for the manner in which the signals could be transmitted to the recording unit.

The connections between the neck, head and stem had to be completely waterproof

The metals usually used for surgical implants were rejected, because they were too weak (18/8 Mo steel), too difficult to machine (cobolt chromium alloys) or had low wear resistance (titanium) If a small amount of titanium is added to stainless steel its strength is increased as well as its resistance to corrosion A titanium stabilized stainless steel was used for the measuring prosthesis

The shape of the prosthesis had to be adapted to anatomical requirements It could not be made especially for the person who would use it therefore the shape and outer dimensions were determined from mean values The diameter of the prosthetic head should be the same as the femoral head it replaces The size most often used in our experience is $1^7/_8$ inch or 47 2 mm The diameter of the head of the measuring prosthesis was chosen to be 47 2 mm

The length of the neck should be as long as possible to deliver strong signals Both the Moore and Thompson prostheses have a distance of 48—50 mm between the vertex of the sphere and the inferior surface of the supporting plate against the neckrest when the head diameter is 47 2 mm

Wertheimer and Martin (1963) determined the distance between the vertex of the femoral head and the point of the outer surface of the femur cut by the longitudinal axis of the neck in 80 specimens They found extreme measurements to be 75 and 110 mm but no information regarding the variation was given No appreciable difference between left and right side of the same subject was found The mean between the two extremes is 93 mm Taking these figures and manufacturing factors into consideration the distance between the vertex of the measuring prosthesis and the supporting surface against the neck rest was chosen to be 68 6 mm

If the distance between the neck rest and the lateral surface of the femur along the longitudinal axis can be approximated to about 25 mm a total length of 93 6 mm occurs

The length of the neck was 30 mm, but if the head was made hollow the neck could pass 10 mm beyond the centre Gauges could be placed in a section through the midpoint of the sphere

The angle between the stem and the neck part of the prosthesis was chosen to be 120° The true cervico-diaphyseal angle is a few degrees greater In both cases however the cervico diaphyseal angle was found to be smaller than that of the opposite side From an anatomic as well as from a recording point of view the cervico-diaphyseal angle of the prosthesis should have been greater

Transmission of the signals from the prosthesis to the recording unit was discussed From the beginning it was thought that telemetry would have been the best method, but it had to be rejected for economical reasons It was decided to have the signals transmitted by leads The leads contained toxic material so they were covered with terylene and teflon At the distal end the leads were connected to a hermetically sealed contact house

The recordings could not begin for a period of time after surgery so the leads and the contact house were left under the fascia for about 6 months Then the contact house was brought out through an incision

When the recordings were completed the leads were removed, close to the prosthesis because they were potentially toxic The prosthesis was provided with a sharp edge at the junction of the leads and the prosthesis in order to cut them free by pulling them against this edge Removal by this method failed because the angle between the leads and the edge was not great enough Removal of the leads required a separate operation Two measuring prostheses have been manufactured and placed into two patients Recordings were begun about six months after the operation The recordings were completed within a week because of the risk of hip-joint infection secondary to the lead tract from the skin surface

Electronic walk-ways

The use of a femoral end prosthesis creates abnormal conditions, which might disturb the function of the hip joint. From experience it is known that the functional results in patients with such prostheses varies There will be patients who have an apparently normal gait and some with a

marked limp An apparently normal gait does not necessarily mean that the gait is normal *A method which makes it possible to determine the* load bearing capacity of the lower extremities has been developed The walk ways and filmtrack described in Part III were constructed to determine the transition between stance and swing phase in both walking and running This is important in the analysis of the forces which act on the hip joint

By means of force transducers the walk ways record the vertical and the horizontal forces (Part III page 65) From the vertical force curves differences of load intensity between the left and the right side could be determined as well as the transition between the stance and the swing-phase

The walk-ways have a relatively low natural frequency of about 50 cps Force sequences of frequency greater than 1/8 of the natural frequency or about 6 cps are not recorded with high accuracy With the exception of the force g of the horizontal curves (Part III page 65) force sequences of more than 6 cps were not recorded Influence of the recordings by the natural frequency of the walk ways is of minor importance since comparisons between left and right side only have been made

Recordings from persons without gait disturbances revealed no difference between the left and right sides Gait disturbance changes the shape and magnitude of the vertical force curves so that in limping, the vertical force is usally smaller on the affected side Sometimes the maximum value of the vertical force is equal on both sides even though both extremities do not carry equal loads The area under the vertical force curve in the stance phase is always diminished in limping, which is a sign of less load per time unit

A limping person always remains longer on the non affected side and his stance phase is diminished on the affected side and prolonged on the good side This means that the swing phase must be prolonged on the affected side and diminished on the good side The created difference between the ratio of stance-phase to swing phase between the two sides becomes a sensitive sign of gait disturbance Another alteration is observed when the distance between the two maximum points *b* and *d* (part III page 89 fig 31) is diminished The foregoing changes are recorded by means of the walk ways

The ratio between the stance phase and the swing phase varies with different walking-speeds

Normally no difference in this ratio between the left and the right side should occur and this index should be 1 0 Tests on normal persons confirmed this Persons with gait disturbances *have an index greater than 1 0,*

especially during slow walking when values exceed 1 5 As the walking speed increases, the index decreases, and if the gait is fast enough the index approaches 1 0 The decreased distance between the points *b* and *d* is not influenced by the walking speed

The two persons equipped with a measuring prosthesis case 1 and case 2 have been tested on the walk ways Differences from normal were found to exist in both cases but they were more pronounced in case 1 where a slight difference of a maximum load of the force F was recorded (Part III page 89) The area this force curve formed in the stance phase was decreased The index of the ratio stance-phase to swing phase between the opposite and the prosthetic sides was increased but during rapid walking the index approached 1 0 The diminished distance between the point *b* and *d* persisted in all tests

In case 2 there was small difference of the maximum value for the vertical force F but the index of the ratio stance-phase to swing phase and the distance between the points *b* and *d* were normal

Simultaneous recordings of the vertical force F from the walk-ways and the forces recorded from the hip joint showed a correlation in time between their maximum and minimum values for the stance phase The transition between the stance and swing phases occurred with changes in the shape of the curves recorded from the prostheses This was more pronounced during running

Recordings from the walk ways were correlated to cinema photography by means of a synchronized watch so that each film frame could be matched to a given point on the force curves The film was exposed at 64 frames per second

When the direction of the forces acting on the hip joint are considered it must be kept in mind that all forces are measured in relation to a coordinate system relative to the prosthesis This makes it necessary to know the size of the angle formed by the thigh and the perpendicular line at heel strike and toe-off This angle might differ from the normal in cases where a femoral end prosthesis is present

The angle (part III page 71 fig 27) which the longitudinal axis of the thigh forms with the perpendicular line the angle v and the angle occurring at the same time between the dorsal thigh and the perpendicular line the angle u have been determined During normal gait the angle v is about 24° and the angle u about 21°

In case 1, the angle v was 24° when the non-operated leg was at heel strike and in case 2 it was 22° These values are normal The angle u at the same time on the prosthetic side was 12° and 19°, respectively The value for angle u obtained in case 1 is not normal When the prosthetic

the longitudinal axis of the femur, the recorded values of the angle γ (part II, page 29) must be decreased by 8°

The cervico-diaphyseal angle of each prosthesis is about 120° (part II, page 58), and if the angle α obtained from the prosthesis shall be compared with the opposite side or another hip joint, the differences of the cervico diaphyseal angles must be accounted for Comparison of the two sides requires the angle α of the prosthetic side to be decreased 10° in case 1 and 20° in case 2

The fit of the prosthesis in the acetabulum is necessary for good function In case 1 the diameter of the prosthetic head was about 3 mm less than the diameter of the femoral head of the opposite side The irregularities occurring during the recording of case 1 could be due to the dissimilarity of the diameters or to minor movements of the prosthetic stem In case 2 there was no measureable difference between the diameters of the prosthetic head and the femoral head replaced by the prosthesis

In addition to the new conditions created by the prosthesis damage secondary to the operation could have had an influence on normal function A dorso lateral approach was used in both cases The gluteus maximus was divided and the small external rotators were cut EMG tests from the abductors adductors and gluteus maximus and minimus showed no sign of neurogenic injury Function of the short rotators was damaged to a certain extent In case 2 there was a decreased ability to externally rotate

Results show differences occurring between repeated tests and between the two patients Some of the differences were due to the different ways of performing the tests Furthermore the lever arms and the direction of muscle pull differs between the two patients

The force acting on the prosthetic head in flexion extension and abduction is large In extension the difference between case 1 and case 2 is marked but it is due to a different technique of extension Case 2 rotated her pelvis when extending the hip In flexion and extension the acting force exceeds the body-weight and in abduction it is about half the body weight Flexion abduction and extension causes a force exceeding that of standing on two legs While walking in a walking support the force is smaller While sitting no force exceeding 12 kp was recorded in either case Of course while changing positions for instance from a bed to a chair the recorded forces were greater

While flexing and abducting the opposite leg the forces acting on the prosthesis were not negligible (part IV page 77 80 and 81) Fig 39 shows the force acting on the hip-joint when subjected to different loads due to shifting of the superimposed bodyweight The test was performed with

the patient standing with each leg on one of the walk-ways shifting his weight from one leg to the other How much of the body weight was supported by respective legs was recorded from the walk ways The force acting on the hip when the walk way recorded no force under the

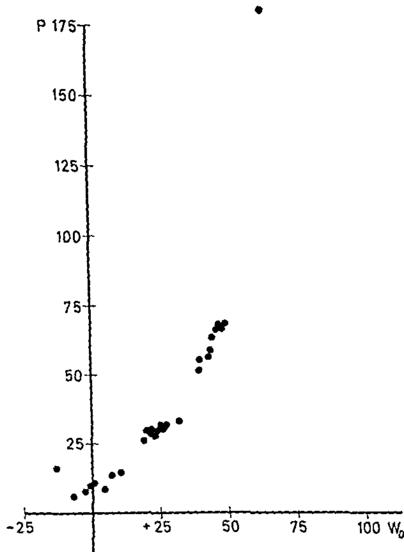


Fig 39 The force acting on the prosthetic head when subjected to different loads due to shifting of the superimposed body weight The weight of each leg is approximated to 1/6 of the body weight The force P is indicated on the y axis and the superimposed body weight W_0 on the x axis The maximum value is for one leg support on the prosthetic leg and the negative x values are for one leg support of the opposite side

prosthetic leg was 0 3 times the body-weight. The discrepancy between this value and that of one-leg support of the opposite leg (part IV page 86) is due to flexion of the knee in the latter test

The force acting in two leg support was close to 0 5 times the superimposed body weight or about 1/3 of the body weight One-leg support gives rise to a high load on the hip One leg support of the opposite side especially in case 2 gives a surprisingly high load on the hip In case 2 this developed with about 90° of flexion in the hip One leg support results in a purely vertical load parallel to the longitudinal axis of the femoral shaft

While walking the hip must resist great forces in both the stance and the swing phase In the stance phase two maximum points with a low point between occur similarly to the vertical force curve describing the action between the foot and the ground At the transition between stance- and swing phase the force in the hip is not zero as the vertical force F is In the swing phase two maximum points with a low point between occurred for case 1 The first maximum point appears immediately after toe-off and the second immediately before heel strike The force at the low point was about zero

In case 2 the transition between the stance- and the swing phase did not cause any changes in the curves, except an occasional decrease in the slope of the curves In the middle of the swing phase a low point Mn, occurred and the forces at this point were about zero The maximum point Mx which occurs in the swing phase and the low point a which occurs at the transition between the swing- and stance phase in case 1 were represented by a plateau in the curves Occasionally however a maximum point was followed by a low point similar to case 1

While walking down stairs (part IV, page 100) the shape of the curves changed in the swing-phase There were two low points recorded and between them a high point Forces present during the swing phase were smaller than those in the stance-phase but sometimes reached values approximating body weight

In case 1 walking tests were performed at two walking speeds The forces present during faster walking were greater, as was expected With a walking speed of 0 9 m/sec. the maximum force was about 1 59 times body weight in the stance phase and 0 59 times body weight in the swing-phase At the speed of 1 3 m/sec these forces were 1 80 and 0 85 times body weight respectively

In case 2 the walking tests were performed similarly to those for case 1 With a walking speed of 1 1 m/sec the maximum force was about 3 0 times body weight in the stance-phase and 1 2 times body weight in the

swing phase At the speed of 1 4 m/sec, these forces were 3 3 and 1 2 times body weight respectively

In case 2 the tests also included running which created forces of 4 3 times body weight in the stance phase and 2 5 times body weight in the swing phase Running speed varied slightly and each speed gave about the same results The maximal recorded value was slightly more than 4 times bodyweight. Very slow walking caused the forces in the stance-phase to slightly exceed body weight Those forces of the swing phase were negligible With use of walking supports the force could be reduced to about 0 3 times the body weight

A study of cane-walking showed that forces in the hip were reduced most when using the cane in the opposite hand If the cane was used in the

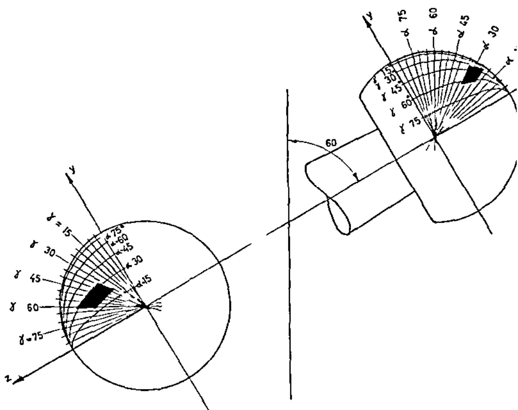


Fig 40 Case 1 Flexion extension and abduction Two views of the prosthetic head each of which is graduated The right view shows the ventral surface of the head as seen from an anterio posterior direction and to the left the surface of the head as seen from acetabulum The area of application of the resultant force as derived from the meanvalue and standard deviation of $\alpha = 28° \pm 5°$ and $\gamma = 47° \pm 15°$ is indicated $n=21$

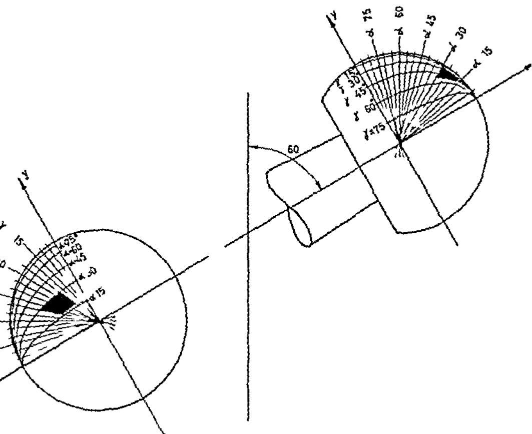


Fig 41 Case 2 Flexion extension and abduction Two views of the prosthetic head each of which is graduated The right view shows the ventral surface of the head as seen from an anterio-posterior direction and to the left the surface of the head as seen from acetabulum The area of application of the resultant force as derived from the mean value and standard deviation of $\alpha = 23^\circ \pm 6^\circ$ and $\gamma = 37^\circ \pm 12^\circ$ is indicated $n = 31$

prosthetic hand, the vertical force between the foot and the ground was reduced on the unoperated side

The coefficient of friction between the steel surface of the prosthetic head and the acetabular cartilage was found to be low, about 0 02—0 04 This is more than double that between cartilage and cartilage but less than that occurring between two lubricated steel surfaces In case 1 the coefficient of friction increased somewhat after walking about 25 m At that point the patient complained of fatigue in the hip This vanished after a few minutes rest and the coefficient of friction returned to its original lower value These findings could not be verified in case 2

In case 1 the coefficient of friction was also determined under static conditions It was found to be about 0 10 which is markedly more than that for dynamic conditions

Traction up to 24 kp for 3 hours applied to the prosthetic leg caused no forces acting on the prosthetic head.
Tests performed on case 1 and 2 on regaining conciousness after anaesthesia revealed no force to act in a relaxed supine position
An interesting observation has been made regarding the direction of the acting forces The area of application of the resultant force is very limited regardless of the head s position in the joint. This means, that the direction of the force is constant in relation to the prosthetic head The area of application is not the same as the contact or compression area but since it is applied between two smooth surfaces it must be the midpoint of the contact area If the surfaces are not congruent, this becomes an area of

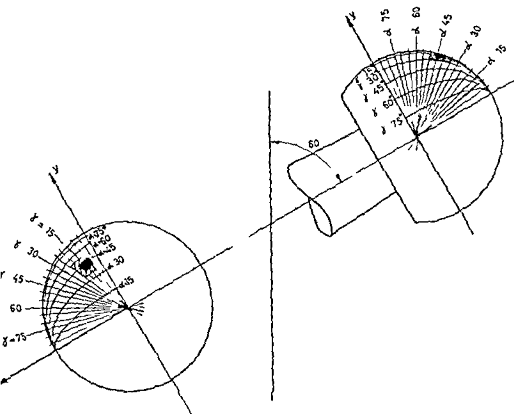


Fig 42. *Case 1 Level walking Two views of the prosthetic head each of which is graduated The right view shows the ventral surface of the head as seen from an anterio posterior direction and to the left the surface of the head as seen from acetabulum The area of application of the resultant force as derived from the mean value and standard deviation of α and γ is indicated The solid black area represents the values α = 43° ± 3° and γ = 15° ± 3° in the stance phase and the striped area the values α = 43° ± 8° and γ = 19° ± 6° in the swing phase n=99 for the stance — and n=66 for the swing phase*

algebraic summation of points resulting from two or more contact areas It is hard to believe that there can be more than one contact area at the same time between the prosthetic head and the acetabulum, and this study indicates that the area of application is the centre of the contact area In fig 40 and 41 the area of application for all tests in flexion, extension and abduction are illustrated This area is derived from a mean value and its standard deviation

In fig 42 and 43 the area of application is derived the same way and illustrates data from the tests of level walking in case 1 and level walking and running in case 2 Values have been taken from all maximum points in the stance- and swing phases and the point c in running also for the

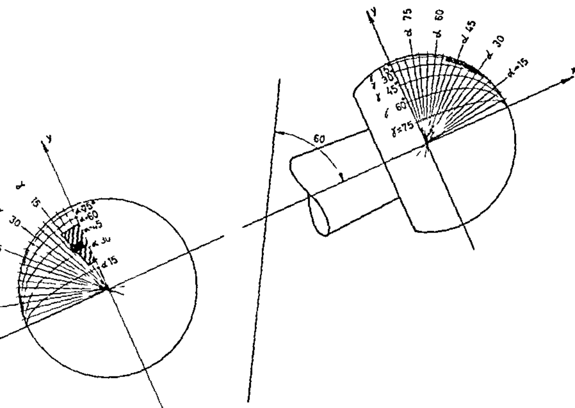


Fig 43 Case 2 Level walking Two views of the prosthetic head each of which is graduated The right view shows the ventral surface of the head as seen from an anterio posterior direction and to the left the surface of the head as seen from acetabulum The area of application of the resultant force as derived from the mean value and standard deviation of α and γ is indicated The solid black area represents the values α = 35° ± 3° and γ = 11° ± 7° in the stance phase and the striped area the values α = 36° ± 17° and γ = 9° ± 8° in the swing phase n=120 for the stance — and n=40 for the swing phase

points *a* and *e* The area of application is small and differs little from that of flexion extension and abduction

In fig 44 and 45 the area of application of the force present in stair walking is shown This area is somewhat larger but involves the usual part of the head

In addition to the force resultant being applied to a limited area on the prosthetic head it was observed that the horizontal component was always applied to the head on its ventral side With exception of the low points which occurred in the swing phase the force was never applied to the head on its dorsal aspect when the patient actively moved the hip To check these results rotation tests were made in case 2 Active internal

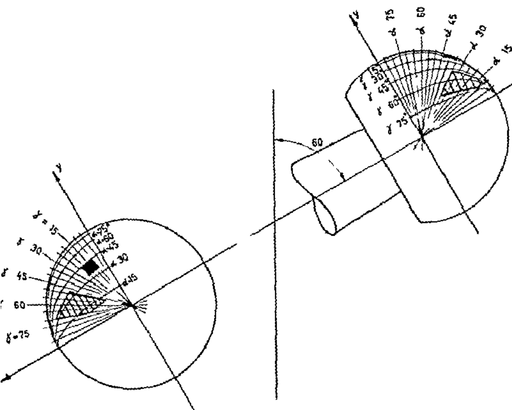


Fig 44 *Case 1 Stairwalking Two views of the prosthetic head each of which is graduated The right view shows the ventral surface of the head as seen from an anterioposterior direction and to the left the surface of the head as seen from acetabulum The area of application of the resultant force as derived from the mean value and standard deviation of* α *and* γ *is indicated The solid black area represents the values* $\alpha = 39^\circ \pm 4^\circ$ *and* $\gamma = 18^\circ \pm 5^\circ$ *in the stance phase and the striped area the values* $\alpha = 23^\circ \pm 11^\circ$ *and* $\gamma = 59^\circ \pm 11^\circ$ *in the swing phase* $n=51$

rotation should cause the head to be pressed against the dorsal part of the acetabulum However, when the patient actively rotated the thigh inwards the force was always applied to the head on its ventral side This occurred whether lying in bed with the hip and knee in the neutral position or while sitting in a chair with hip and knee flexed If the patient was told to relax passive internal rotation created a force which now was applied to the head on its dorsal side From this it is concluded that moving the hip actively causes the force always to come from the ventral side With the hip flexed while supine the force had the same direction as in extension while prone

The limited direction of the force in relation to the prosthetic head surface

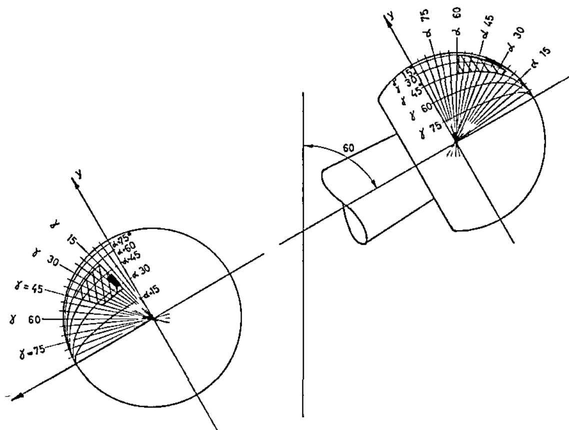


Fig 45 *Case 2 Stairwalking Two views of the prosthetic head each of which is graduated The right view shows the ventral surface of the head as seen from an anterio posterior direction and to the left the surface of the head as seen from acetabulum The area of application of the resultant force as derived from the mean value and standard deviation of* α *and* γ *is indicated The solid black area represents the values* $\alpha = 36^\circ \pm 5^\circ$ *and* $\gamma = 15^\circ \pm 2^\circ$ *in the stance phase and the striped area the values* $\alpha = 42^\circ \pm 15^\circ$ *and* $\gamma = 30^\circ \pm 15^\circ$ *in the swing phase* $n=50$

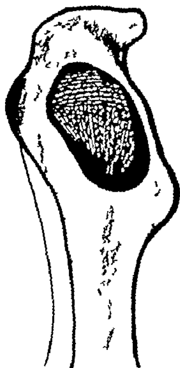


Fig 46 *In a cross section through the junction of the femoral neck and shaft the lamellae assume the shape of a T beam*

is in accordance with some details of the anatomy of the upper femur and also with findings in some pathological conditions associated with decreased resistance against mechanical factors The femoral neck is not a true cylinder but reveals an elliptical cross section This elliptical shape is less pronounced near the head, but increases in distal lateral direction The major axis of the elliptical cross section forms an angle opening dorsally relative to the shaft. This gives maximum resistance to a force parallel with the major axis Such a force will be applied to the femoral head on its ventral aspects Furthermore the structural resistance increases in the distal lateral direction to counterbalance the stresses present in this type of cantilever

It is interesting to note that a cross section taken through the neck close to the shaft reveals the lamellae of the spongiosa to run in such a way that its design is in the form of a T (fig 46) This could mean that the spongiosa at this level acts as a T beam to give high resistance to vertical loading Since the base of the T comes from the lateral trabecular portion and the upper part of the T from the arcuate portion this could be one explanation of the function of the two systems The upper part of the T will resist tensile stresses and the lower part compressive stresses The

direction of each part of the T coincides approximately with the direction of one of the two axes of the cross sectional ellipse.

The antetorsion usually seen in the upper femur presents a high resistance to any horizontal force applied to the head on its ventral aspects

Clinically, the presence of a ventrally acting force may help to explain why femoral head displacement is always dorsal in femoral neck fractures and in slipped capital femoral epiphyses

In some pathological conditions where tissue alteration occurs secondary to mechanical factors, X ray changes are often seen in an area corresponding to the force area of application

In coxa plana indentation and fragmentation are usually found in this area (Edgren 1965)

Trueta et al (1953, 1954) described an area in which they found pathological changes in osteoarthritis of the hip This area, which they called the compression area, is described by a U shape and covers the upper ventral and dorsal aspects of the femoral head

A review of X rays of osteoarthritis in the hip joint shows the first sign of indentation occurring on the ventral side of the longitudinal axis of the femoral neck in the lateral views

One of the first signs in X-rays where necrosis of the femoral head is present usually is a compression in the circular outline of the head in the same area as the area of application of the force Examination of excised necrotic femoral heads usually shows a compressed area most pronounced in the predicted area

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HENRY BRUMMER

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FROM THE DEPARMENT OF FORENSIC MEDICINE, UNIVERSITY OF HELSINKI, (HEAD PROFESSOR UNTO UOTILA, M.D.) AND FROM THE CLINIC FOR *ORTHOPAEDICS AND TRAUMATOLOGY UNIVERSITY OF HELSINKI (HEAD* PROFESSOR K. E. KALLIO M.D.)

THE ADHESIONS OF A TRAUMATIZED TENDON FORMED UNDER THE EFFECT OF THYROTROPIN AND SOMATOTROPIN

EXPERIMENTAL STUDIES BY PHYSICAL AND HISTOQUANTITATIVE MEASUREMENTS

by

HENRY BRUMMER

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Helsinki May 1966

Henry Brummer

CONTENTS

1 INTRODUCTION

When one considers the development of medical science especially that of surgery there is no need to go very far back in time before a point is reached at which it is appropriate to state that virtually all existing knowledge had been gathered by empirical means Figuratively speaking each investigator describing his own cases and methods had contributed his own grain of sand to the heaped knowledge But the higher such a sand dune of empirism becomes the greater is the toil facing one who wants to plod through it and ascend to the top This is because there is no solid foundation

Traumatology is originally a by product of military campaigns where else in earlier days could one have found injuries of the most varying kind in such accumulation? Men of high morals splendid intelligence and industry such as AMBROISE PARÉ (1517—1596) and JEAN DOMINIQUE LARREY (1766—1842) were compelled to work exclusively on an empirical basis For this reason they were unable to give surgery any firm standing like that enjoyed by the natural sciences

The surgeons working around the turn of this century (v BERGMANN 1887 LEXER 1911) observed that wounds heal in one of two ways either »per primam intentionem» or »per secundam intentionem» These concepts had originally been presented by GALEN Even nowadays the surgeon may express his satisfaction by saying that the wound »granulates nicely» by which he means that the repair process has overcome the inflammation (BOYD 1947)

However the actual development of surgery cannot be based on wartime surgical experience which obviously implies reconcilement with imperfect conditions (FALTIN 1937) In our present days the increasing number of traffic and industrial accidents actually provides a more than adequate wealth of traumatological material for surgical research This has for some time been an inducement to subject the systemic and local factors affecting the healing of wounds to experimental study although it is true that such studies have been descriptive in character in most instances

The formation of granulation tissue was found to be detrimental This

is clearly evident particularly in plastic surgery (GILLIES 1923) in which other requirements apply than in surgery involving the body cavities In the extremities, the scar consequent on granulation is frequently an impediment to appropriate function Thus, restoration surgery has appeared as a companion to traumatic surgery Its most exacting branch is no doubt that of hand surgery, among whose promoters there may be mentioned e g BUNNELL (1921) ISELIN (1938) and MASON (1941)

Granulation tissue is indispensable for the repair process, but at the same time it produces detrimental cicatrization Particularly in the complex plait work of the tendons a scar formed by connective tissue may cause adherence of the tendon to its surroundings thus impeding its function One of the most difficult problems in hand surgery has been to control the formation of scars and adhesions and a great variety of expedients is employed to this end

An altogether new possibility of controlling the scar and adhesion formation was opened up by the observation that the development of granulation tissue could be controlled with the aid of hormones The earliest attempts to exert an influence on the formation of granulation by endocrine means consisted of glandular tissue transplantations (AIEVOLI 1923 KOSDOBA 1934) in contrast to ectomies of endocrine glands After cortisone and corticotrophin had been isolated, these were initially successfully used against rheumatic granulations (HENCH KENDALL, SLOCUMB and POLLEY 1949) The indications of cortisone in surgery and traumatology are about to become definitely clarified and its application has also been tried out in hand surgery (HOWARD BUNNELL and PRATT 1953)

In addition to cortisone, extracts of the anterior hypophysis have been found to exert a notable effect on growth and on the development of granulation tissue (EVANS and LONG 1921) Among the hormones extracted from the adenohypophysis somatotropin and thyrotropin have consider able influence on the granulation tissue according to present concepts (ASBOE HANSEN 1954) However their effect on tendon adhesions has not yet been studied The work presented in the following is thought to throw additional light also on the effect exerted by somatotropin and thyrotropin on the granulation tissue and on wound healing

In the present work the attempt has been made to elaborate a method enabling the hormonal effects to be clarified by examination of the changes they produce in the physical properties of the tissue, together with plani metric measurements and application of histological tissue analysis, and comparison of the results obtained by different approaches

2 REVIEW OF LITERATURE

2.1 Means employed to counteract adhesions

How to restore a tendon s ability to slide is still one of the problems which have not been completely solved In spite of advanced surgical and operating theatre techniques the observation is sometimes made even nowadays to the patient s and surgeon s great displeasure that an extremity has stiffened to immobility and is unfit for use In many instances this has been found to be due to massive adhesions which are formed around an injured tendon and attach it firmly to the surrounding tissues thus inhibiting its motion and frequently also that of other tendons depending on its function In such cases the ultimate outcome of surgical reconstruction has only been worsening of the condition

Very great pains have been taken in order that the formation of detrimental adhesions might be prevented The expedients by which one tries to counteract their formation can be classified as follows

(1) Methods of operating technique
(2) Placing of an interposition
(3) Physiatric methods
(4) Administration of diuretics
(5) *Interference with the sympathetic nervous system* and
(6) Application of hormones

(1) Bunnell (1921) elaborated an operating technique which he calls the »atraumatic technique» Among other things it implies a bloodless operating area and the use of small smooth instruments of suturing material that does not cause any irritation of tissues and of wetted gauze pads Furthermore he described the methods which have to be used in dealing with the skin tendons and nerves This operating technique gave rise to an entire new branch of surgery referred to as hand surgery It has subsequently been further developed by Littler (1947) Mason (1955) Allen (1955) and Verdan (1951)

(2) Organic as well as inorganic substances have been used as interpositions between the tendon and its sheath so that the formation of adhesions might be prevented. HENZE and MAYER (1914) used sections of the peritoneum and of the vena cava for this purpose. WILMATH (1937) made experiments with the tunica vaginalis while WECKESSER, SHAW, SPEARS and SHEA (1949) used autogenous fascia and tried out various kinds of fibrin films. The results were not satisfactory, nor is any organogenic substance being used generally.

Of the inorganic substances tested for their capacity of acting as interposition, the metal tubes surrounding the tendon may be mentioned which were employed by McKEE (1945). Cellophane was tried out by WHEELDON (1939). STINCHFIELD (1950) used a cellulose tube and LEVEEN and BARBER (1949) employed various kinds of plastics such as nylon, polyethylene and Teflon. GONZALES (1949) made a comparative study of various substances used for interposition, including gelatine tubes, cellulose acetate, gelfoam and fibrin film, and with polyethylene. He found that as a rule adhesions due to foreign body irritation and exceeding those recorded in the controls were produced in the presence of the said substances. Only with polyethylene a satisfactory result was obtained in a few cases after an immobilization period of excessive length. MOBERG (1951) stresses the fact that a film enclosing the tendon will cause nutritional disturbance and necrosis, for which reason it is possible to use such films at the most on one side, e.g. as a temporary interposition against bone. ASHLEY, STONE, EDWARDS and SLOAN (1960) conducted tests with cellulose filter, which was porous and permitted diffusion to take place, but this method has not been generally adopted in tendon surgery either.

(3) Physiatric methods aim in the first stage at prevention or reduction of oedema formation and, later, at obliteration of the oedema and detaching of the tendon from such adhesions as have already formed. BLAIR (1943) pointed out that the post-reconstructive surgery oedema is an obstacle to motion already for mechanical reasons and therefore promotes the consolidation of adhesions. He introduced an elastic compression bandage with a view to counteracting the occurrence of swelling. MOBERG (1951) places weight on elevation and muscle movements as factors keeping the oedema-removing venous pump in operation. KOCH (1931), MASON (1955) and PULVERTAFT (1948) demonstrated both empirically and experimentally the important role played by active mobilization in restoring the tendon's sliding capacity. Counteraction of oedema and mobilizing therapy are essential aids in tendon surgery.

(4) Diuretics are used with the intention of reducing the oedematic state and the sodium retention The best diuretics affect directly the kidneys increasing the excretion of water and sodium and preventing the reabsorption of sodium in the kidneys An oedematous state due to accumulation of extracellular fluid is encountered in congestive diseases of the heart in nephrosis and in cirrhosis of the liver all of them diseases which constitute the most important indication for the use of diuretics (GROLLMAN 1960) The effect exerted by diuretics on a local oedema produced by other causes is less pronounced and no influence on the peripheral circulation in the extremities has been noted (MENDLOWITZ NAFTCHI GITLOW, WEINREB and WOLF 1960)

(5) The theory presented by LERICHE (1930) is widely known according to which pain produces a reflex in mentally sensitive individuals By way of the sympathetic nerve tract this results is vasospasm oedema and trophic disorders The immobilization and articular stiffness due to pain lead to oedema which is further acerbated by vasoconstriction The condition is moreover aggravated by increase of the reflectory myogenic tonus The vitious circle built up in this manner promotes the adhesion of the injured tendons to their surroundings The school of LERICHE (1939) fights this by means of interference with the sympathetic nerve system

(6) After the effect of cortisone hydrocortisone and corticotrophin to prevent the formation of granulation tissue became known (RAGAN HOWES MEYER PLOTZ and BLUNT 1949) clinical and experimental study were also directed on their effect upon tendon adhesions STINCHFIELD (1950) applied cortisone locally and generally in order to counteract detrimental formation of connective tissue GONZALES (1953) made experimental studies with dogs flushing with hydrocortisone the tendons injured at operation He could not observe any changes in the formation of adhesions The extensive studies carried out by CARSTAM (1953) showed that the adhesions of rabbits tendons treated with cortisone had lowered tensile strength At the same time however he found that the tendon sutures tended to fail ZACHARIAE and ZACHARIAE (1955) and BANG and SURY (1958) made trials with hydrocortisone treatment in Dupuytren s contracture The opinion stated by POTENZA (1962) is thought to be prevalent that corticoids possess some significance after tenolysis operations but that their application immediately after tendon reconstruction cannot be considered a sound principle on account of separation of the tendon fragments and the risk of infection

Cortisone is by no means the sole hormone exerting a notable effect on granulation tissue Despite the synergy existing between different hormones the effect of other hormones on tendon adhesions has not been investigated

2 2 Healing of the wound

2 21 Formation of granulation tissue

The granulation tissue coming into existence around an injured tendon conforms to the same laws as wound healing in general This biological phenomenon has been and still is one of the central problems in surgery

The wound area is immediately filled by coagulated blood clots and fibrin formations deposited there by the damaged blood vessels It is not positively known what agent puts the wound repair under way According to earlier assumptions some external stimulus would be involved (CARREL 1921) In all likelihood however, a local stimulus seems to be concerned, arising from wound secretions or from cellular destruction (HEGEMAN TRANT and v WALLENSTERN 1950 ZEDERFELDT 1957) This factor set free from the cells or intercellular matter has been called »split protein» (BIRD and MACKAY 1932) It has been said that although the primary precise stimulus is not known the best way to evoke an ideal fibroblastic response is a clean sweep of the cold knife (DUNPHY 1963)

The process commencing in the blood and fibrin coagula accumulated in the wound is known as fibroplasia The source has not been fully clarified from which fibroblasts are supplied to the wound They appear there about 72 hours after the trauma (McDONALD 1959) The fibroblasts have been suggested to come from the loose connective tissue of the organism (HOWES 1954), from the fibrous tissue cells in the adventitia of arteries and veins (McDONALD 1959) or from the mononuclear cells of the blood (ALLGOWER 1956) It is not possible by existing means to differentiate between the proliferative response of the capillaries to trauma and newly formed fibroblasts (GRILLO 1964) It may also be considered an established fact that new fibroblasts are not produced from differentiated connective tissue such as fascia ligaments dermis of the skin, or bones Mature, differentiated connective tissue has a slow metabolic rate and is no longer

able to produce young dedifferentiated fibroblasts (HOWES 1954 EDWARDS and DUNPHY 1958)

It has been shown by tissue cultivation that fibroblasts synthetize certain carbohydrates and proteins (DUNPHY and UDUPA 1955) The suggestion has also been made that mast cells, which obviously synthetize at least heparin participate in the process (JORPES HOLMGREN and WILANDER 1937) A hydrophilous colloid the »ground substance» is formed in the interstices between cells from the original exudate by synthetic action of the fibroblasts It contains mucopolysaccharides and is held together by a network composed of proteins (DORFMAN 1954 MEYER 1954)

The network holding the ground substance together consists of collagen, reticulin and elastic fibres Of these the reticulin obviously has the largest mucopolysaccharide component The polypeptide molecules of the elastin are disoriented, and their chemistry is still largely unclarified (ROBB-SMITH 1954)

Fibroblasts have been found to be indispensable to the generation of collagen (STEARNS 1940 DUNPHY and UDUPA 1955) It is obvious that the biosynthesis of collagen taking place in the fibroblasts includes the same biochemical processes as any other protein synthesis The ribonucleic acids (RNA) and in the final analysis the DNA of the nucleus are thus the agents determining the course of the enzymatic reaction in the endo plasm by which collagen is ultimately produced from hydroxyproline and hydroxylysine (DUNPHY 1963) This »collagen unit» synthetized by the fibroblasts is secreted into extracellular space and only here occurs formation of fibrils (Ross RUSSELL and BENDITT 1962) The last mentioned authorities were able to observe collagen fibres on the surface of fibroblasts by electron microscopy (Ibid 1963)

Investigation of the cell metabolism reveals that ribonucleic acids are formed at liveliest rate in the healing wound after five days The rate of formation goes down after 11 days (WILLIAMSON and DUSCHLBAUER 1963) Correspondingly the mucopolysaccharides in the ground substance begin to decrease after five days (KASAVINA LIRZMAN and MUZIKANT 1959) *After five days collagen can be demonstrated by usual histological expedients* (DUNPHY ENGLEBERT and UDUPA 1955) The collagen concentration increases rapidly during the period from 5 to 14 days (JACKSON 1958) whereafter the process slows down

The appearance of collagen in the granulation tissue is a sign of its incipient maturation It is also one of the most essential events in wound healing from the clinical point of view

2 22 Phases of wound repair

The healing of wounds is of utmost significance in surgical practice and in clinical research Accordingly, this biological process is a subject of continuous, active research CARREL and DUNOUY (1921) observed in their clinical studies a so called latent period in wound healing beginning at the time of trauma and terminating when the wound starts to contract The latent period had a duration of 5—7 days whereafter it ended abruptly and wound contraction commenced at full force Every surgeon has been able to learn empirically that a wound may open up again if the sutures are removed before the fifth day FORSSELL (1960) found with human patients that a scar after laparotomy does not hold until on the sixth day, up to that time the wound is kept closed by the suture alone WHIPPLE (1940) says with emphasis that the critical latent period or »lag period», is the touchstone of surgery in that the wound is kept closed during this period by surgical means

This does not imply that there would be any metabolically inactive lag phase RAEKALLIO and LEVONEN (1963) were able to demonstrate by enzyme histochemistry the presence of adenosine + ribophosphatase activity as early as one hour after the trauma Aminopeptidase activity was already encountered after two hours, and a couple of hours later other enzyme activities could be established as well (RAEKALLIO 1961, MONIS 1963) During the clinical lag period a biological process is gone through of which the end result is evident in the clinical physical ways described

The terminology referring to a latent period or »lag phase» has been used by numerous investigators in their division of the wound healing into different phases (HOWES, SOOY and HARVEY 1925 WHIPPLE 1940 RAEKALLIO 1961 SANDBERG 1963) In experimental studies a division based on histological observations is to be preferred Among several suggested divisions that presented by DUNPHY and UDUPA (1955) and by EDWARDS and DUNPHY (1958) has been employed in the present work Accordingly the following two phases are distinguished in wound healing

(1) the productive or substrate phase,
(2) the collagen phase

The first phase lasts for about five days counted from the trauma during this time exudation occurs at first Lively fibroblast proliferation ensues and mucopolysaccharides and soluble collagen precursor are formed

Evidence to the same effect is furnished by abundant formation of ribonucleic acid noted after five days (WILLIAMSSON and GUSCHLBAUER 1963)

In the second phase after five days have passed collagen fibres can be histologically observed in the wound Since there is such a sharp demarcation between the productive and collagen phases some authorities maintain that the granulation tissue present during the first phase would be completely incapable of collagen formation for which the healthy fibro blasts in adjacent areas would be responsible (WATTS et al 1963) It is indeed a fact that in some instances e.g in granulomas for some reason no collagen is formed The collagen concentration rapidly increases during the period between 5 and 14 days (JACKSON 1958) After that the growth becomes slower and gradually ceases The wound has then attained the stage of full maturity (WHIPPLE 1940)

2 23 *Factors affecting the healing*

Local factors

The factors exerting an influence on the healing of wounds may be divided into local and systemic factors The wound is most susceptible to external influences during the productive phase of wound healing that is at its initial stage

SAUERBRUCH (1924) BIRD (1932) BUNNELL (1944) and FORSSELL (1960) have observed that the healing of a wound is dependent on the *quantity of destroyed tissue* in the wound It is delayed by the local, proteolytic ferments produced in destroyed tissue (BENZER, BLÜMEL and PIZA 1962) Even mere touching of the wound with a gauze pad adds to the trauma causing slower wound healing and a greater amount of scar tissue By means of careful measurements SANDBLOM and MUREN (1954) found that even such a minute circumstance of *operating technique* as the side on which the operating surgeon was sitting had a distinct influence on the healing of the wound BIRD and MACKAY (1932) and WHIPPLE (1940) stress the extraordinarily powerful effect of *local infection*, which is evident in delayed healing and increased scar tissue. Any factor affecting the *local circulation* causes slower wound healing SANDBLOM and MUREN (1954) noted that the method used *in shaving* the experimental animal s hair and the time at which this was done affected the wound healing This was attributed to cooling of the skin and attendant vasoconstriction LUNDGREN MUREN

and ZEDERFELDT (1959) reported that vasoconstriction induced by *cold* also disturbed the healing The experiments of BODVAL and RAIS (1962) proved that local injection of a *vasoconstrictor* distinctly impaired the wound healing SUNDBERG and ZEDERFELDT (1959/60) noticed poorer wound healing when profuse *acute haemorrhage* had caused superficial vasoconstriction BIRD and MACKAY (1932) observed effects exerted by various kinds of *radiation* on wound healing FINDLAY and HOWES (1950) also found that local *oedema* increased the fibroplasia *Mechanical or chemical irritation* of any other kind also affects the healing process (FORSSELL 1960) For instance antiphlogistics introduced into the wound had an inhibiting effect on the granulation formation (RUDAS 1963) CARREL (1921) DUMONT (1959) and PAULETTE (1959) stated that *foreign bodies and substances* in the wound cause irritation and disturb the normal healing This has to be taken into account especially in choosing the suturing material (BUNNELL 1944)

Systemic factors

The systemic factors affecting the healing of wounds include the age and above all, various states of deficiency and diseases

High *age* causes delayed wound healing (BIRD and MACKAY 1932 FORSSELL 1960) while the wounds of young individuals heal with remarkable speed The duration of the productive phase obviously becomes longer with increasing age After this phase has been passed, repair will progress at equal speed in young and old (HOWES and HARVEY 1932) The rate of cell division is inversely proportional to age a fact which CARREL (1921) attributed to some inhibitory factor increasing in strength with age TEIR and NYSTROM (1962) observed that skin homogenisate derived from new born rats promoted the healing of wounds An assumption has been presented concerning the existence of a growth promoting factor, which becomes less with increasing age of the individual (YOUNG, FISCHER and YOUNG 1941)

The importance of *diet* with regard to undisturbed wound healing has long been known (SAUERBRUCH 1924) The retarding effect of *starvation* on the healing of wounds became evident when the experimental animals' weight had gone down 20 % The albumin in the blood was found to decrease at this stage FINDLAY and HOWES (1950) also stated that they observed reduced tensile strength of the wound tissues on *low protein*

diet The attendant oedematic state increased the fibroplasia DUNPHY and UDUPA (1955) noted that the productive phase of wound healing was longer in duration on low protein diet KOVAK BENDITT WISSLER and STAFFEE (1947) ascribed this to retarded collagen formation

Disturbed *liquid and electrolyte balance* causes the productive phase in wound healing to take longer (WHIPPLE 1940) Potassium deficiency delays the healing slightly (FINDLAY and HOWES 1950) Also dehydration has been found to lower the strength of the wound (BIRD and MACKAY 1932)

Anaemia and *acute haemorrhage* have also some effect on wound healing (SANDBERG and ZEDERFELDT 1959, FORSSELL 1960)

Distinct influence of *vitamin deficiencies* on the healing of wounds has been established SCHAUBE CHEN POSTLETHWEIT and DILLON (1960) observed that ascorbic acid accumulated in the wound in great quantity during the repair period its need was strongest from the fourth to fourteenth day ROBERTSON and SCHWARZ (1953) have found that ascorbic acid is indispensable in collagen synthesis ROSS and BENDITT (1963) reported that extracellular collagen fibrils are not encoutered in wounds of scorbutic animals until they are given ascorbic acid

Cytostatics have been noted to disturb but not to prohibit entirely the wound healing process (TALA and KERMINEN 1963) Changes in the rate of wound healing have been obtained with a great variety of *drugs* (FENTON and WEST 1963) BIRD and MACKAY (1932) stated that they observed delayed wound healing in certain *chronic diseases*, such as diabetes and nephritis

2 3 The healing of an injured tendon

2 31 Histological nomenclature

A tendon is composed of collagen fibre bundles between which the flattened cells are found The bundles are mutually separated by the thin e n d o t e n o n consisting of more delicate connective tissue The surface of the tendon is covered by the e p i t e n o n consisting of mesothelial tissue When the tendon runs straight it is encircled by a loose movable fat tissue the p a r a t e n o n which follows the tendon in its movements If the tendon has to make a bend it is enclosed by the t e n d o n s h e a t h at such points On the concave side of the bend originates the bifoliate m e s o t e n o n which directly joins the epi

tenon of the tendon The inner surface of the tendon sheath is lined by the peritenon to which the mesotenon attaches In the tendon sheath the blood vessels have access to the tendon only along the meso tenon while a paratenoneal tendon is reached by blood vessels from all sides

2 32 Repair of a tendon

Much speculation has been called forth by the question of how an injured tendon is repaired because a rather highly differentiated tissue is concerned which is a fairly specific kind of connective tissue

(a) SEGGEL (1903) and GARLOCK (1927) considered that *regeneration* of the tendon proceeds from the tendon itself As a consequence of primary, reactive hyperaemia a blood and fibrin clot is formed which becomes organized from the tendon the fibroblasts would then start at the tendon fragments in the endotenon and epitenon This non specific tissue would later be replaced by tendinous tissue coming from the tendon The tendinous tissue itself undergoes a process in which it swells and softens at first, on the fourth day and the contours of its cell nuclei become indistinct At a later stage the swelling abates and the cells regain their normal appear ance – The theory ran up against difficulties when it was found that the repair of tendons enclosed in a tendon sheath progressed more poorly BIER (1920) attributed the slow growth to a hormone like substance contained in the synovial fluid WEHNER (1922 1923) and HUECK (1923) were able to disprove the existence of any such specific substance in the synovial tissue HOWES (1954) and EDWARDS and DUNPHY (1958) showed that no new fibroblasts are produced by highly differentiated tissue such as the tendon The theory of the tendon tissue s active participation in the regeneration process has been discarded for these reasons (SKOOG 1954)

(b) MASON and SHEARON (1932) and MASON and ALLEN (1941) arrived at the conclusion that both the undifferentiated connective tissue around the tendon and the tendinous tissue itself participate in the regeneration They divided the repair process into two phases The first would be the connective tissue phase at which the connective tissue within upon and around the tendon proliferates and the fibroblasts form a collar like scar between the fragment ends At the second phase the tendon itself would start to proliferate after about 4—5 days The proliferation of the connective tissue terminates after about two weeks whereas the second phase continues

and the so-called tendon callus is formed The authors strive for analogy with the process of bone repair by which they explain the conversion of the tendon scar into firm tissue resembling that of the tendon

(c) The participation of the tendon in the regeneration process is altogether disputed by numerous authorities WEHNER (1923), HUECK (1923) NARVI (1926) SKOOG and PERSSON (1954), DAVIDSSON (1956) ASHLEY STONE EDWARDS and SLOAN (1960) and POTENZA (1962) observed that at the beginning a fibrin precipitate was established between the fragments of the severed tendon When it became organized the connective tissue invaded it from the side The fibroblasts grew from the paratenon outside the tendon in between its fragments and even penetrating into the tendon until they encountered the intact endotenon SKOOG (1954) was able to demonstrate that only degenerative changes take place in the tendinous tissue such as swelling and hyalinization of collagen fibrils with associated pyknosis and karyorrhexis of tendinous cells

Tendorrhaphy had no noteworthy effect on the repair process proper In that case too the connective tissue penetrated from the side into the space between the sutured tendon fragments At the most suturation further lowered the vitality of the tendon

NARVI (1926) noticed that the epitenon was only able to form a thin layer at the end of the injured tendon fragment while the main regeneration took place from the peritenon and from the surrounding connective tissue

When SKOOG (1954) damaged the surface of the tendon by removing its epitenon strong formation of adhesions was observed and the para tenon invaded the tendon at this point too Similarly MASON and ALLEN (1941) admit that damage to the epitenon of the tendon produces adhesions

The above mentioned investigators also found that if a damaged tendon is subjected to stress at a time earlier than two weeks after the injury increased reaction occurs at the point of trauma and heavier adhesions are formed

WEHNER (1923) and HUECK (1923) observed that the motion of the tendon only very slowly imparts to the fibres of the scar tissue in the tendon a consistent orientation by which the scar begins to resemble a true tendon MASON and ALLEN s (1941) studies reveal that the tensile strength of the tendon suture in tension tests became lower within five days after which it began to increase once more If the tendon was not stressed at all the tensile strength of the sutured point ceased to increase

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after the sixteenth day Light stress applied from this time onwards con tinuously augmented the tensile strength, and by this procedure the smallest scar was also obtained This finding is supported by the writer s own clinical observations

2 4 Influence of hormones

In addition to the factors considered in the foregoing, also hormones have been found to exert an effect on the healing of wounds When the influence of hormones on connective tissue are to be investigated the fact should be borne in mind that the well known laws governing the general action mechanism of hormones are valid in this domain too

(1) Hormones cause no unique biochemical reactions but they affect the intensity and rate of existing reactions They have been likened to catalysts in this respect

(2) In some intances a given hormone may be antagonistic to another hormone and it may be synergistic with regard to a third one Changes in the concentration of some hormone in the blood may therefore result in strengthened or lowered effect of this particular hormone depending on the quantity of synergistic or antagonistic hormone that is secreted (Williams 1955)

It is obvious that in addition to the adrenal corticosteroids, thyrotropin and somatotropin have a remarkable influence on granulation tissue (Asboe Hansen 1954)

2 41 *Somatotropin*

Growth hormone (GH), or somatotropin (STH) is a secretion of the eosinophilic or acidophilic cells in the so called adenohypophysis of the anterior hypophyseal lobe It has been known under the name of growth hormone since Smith (1927) observed that extract from the anterior hypophysis restored normal growth in hypophysectomized animals Since growth is also greatly dependent on a number of other hormonal factors, the name has later been changed into somatotropic hormone (STH) or somatotropin Somatotropin is one of the so called protein hormones, its physical and chemical characteristics clearly indicate that the somatotropin preparations obtained from the hypophyses of different animal species are different proteins The somatotropins of the primates have the lowest molecular weight and isoelectric point but not even the protein hormones of as closely related species as man and ape are identical (Li 1960)

Metabolic effects The metabolic effects of somatotropin concentrate on the protein metabolism calcium metabolism sodium and chloride metabolism, fat metabolism ketogenesis and carbohydrate metabolism as their targets The effect on the protein metabolism is anabolic causing retention of nitrogen phosphorus and potassium Somatotropin affects the calcium metabolism by increasing the calcium excretion with the urine and accelerating the metabolism of bone (DENKO and BERGENSTAL 1955) Retention of sodium and chlorides occurs during somatotropin administration and the intercellular fluid quantity increases Fat is mobilized in the tissues under its effect In the carbohydrate metabolism a diabetogenic factor is encountered in somatotropin which aggravates the disease of diabetics (IKKOS LUFT and GEMZELL 1958)

Biological effects Somatotropin produces remarkable increase of growth in hypopituitary dwarfs (BLIZZARD 1963) The blood plasma of children and subadults has been found to contain twenty times as much growth hormone as that of adults (GREENWOOD HUNTER and MARRIAN 1964) Growth hormone is reported to stimulate the formation of granulation tissue in infected tissues (TAUBENHAUS and AMROMIN 1950) In mycotic infections of rats CAVALLERO (1953) observed stimulation of connective tissue formation by somatotropin, resulting in powerful connective tissue proliferation around the infected tissue. No effect on the agent responsible for the infection such as the tuberculosis bacillus was observed by WASZ HOCKERT (1963) According to WILLIAMSSON and NEUMAN (1954) small somatotropin doses appear to be optimal whereas larger doses cause inhibition SPAIN and MOLOMUT (1953) did not succeed in producing stimulation of granulation tissue in mice with somatotropin Somato tropin did not increase the growth in tissues inhibited with cortisone KOKKONEN (1963) actually noted initial decrease of the connective tissue formation in a tuberculous gland On the other hand TAUBENHAUS TAYLOR and MORTON (1952) established a stimulating effect of somato tropin in granulations which had been subjected to inhibition by cortisone

TAUBENHAUS (1950) found that in rats to which somatotropin was given granulation tissue was formed more abundantly in turpentine abscesses than in normal rats The walls of the abscesses became thicker the fibroblasts were large and multipolar Multinuclear giant cells also occurred Pale homogeneous collagen was abundant

Specific effects on granulation tissue WEGELIUS and ASBOE HANSEN (1956) observed under somatotropin effect increased formation of muco-

polysaccharides as a result of mast cell stimulation TAUBENHAUS and AMROMIN (1950) found that somatotropin stimulated the fibroblast proliferation Scow (1951) observed in thyroidectomized rats increase in collagen formation in skin and muscles It should be noted that thyroidectomy considerably accelerates the thyrotropic hormone secretion of the hypophysis and that many somatotropin extracts are thyrotropin contaminated (ASBOE HANSEN 1959) BANFIELD (1958) studied with hamsters the collagen extracts of skin and found that the acid soluble collagen quantity increases with age. Daily somatotropin injections increased the collagen concentration BANFIELD discussed the question whether the increase was due to change of old or precipitation of new collagen and whether the effect of somatotropin was a direct one or was produced by mediation of one or several endocrine glands SAIKKU (1956) observed with rats that somatotropin at first increased the quantity of granulation tissue but that the difference with regard to the controls levelled out in more mature granulations To start with the granulation tissue was similar to that of the controls, but at a later time collagen fibrils occurred in greater and intercellular substance in smaller amount than in the controls GYLLING (1964) elicited no changes with somatotropin injections administered to rats in the intraabdominal adhesions which had been induced in them Only in combination with thyrotropin was ground substance produced in considerable quantity

Effect on bone LENTIN and SUMMA (1958) observed that somatotropin injections promote the formation of new bone in fractures This was attributed to its action on cartilage Somatotropin appears to have chondrotrophic effect KOSKINEN (1959) found that somatotropin caused powerful osteogenesis in the reparative phase of experimental fracture repair resulting in rapid callus formation and maturation of the callus tissue In studies by electron microscopy of the cartilage developing under somatotropin effect SILBERBERG et al (1964) observed hyperplasia and hypertrophy of chondrocytes and accelerated ossification They call particular attention to the fact that the fibrillar content of the matrix increased and the development of the collagen fibres was accelerated The cartilage matured and aged as evidenced by disorientation, »asbestosis», of collagen fibres In their discussion of the problem they ascribe the phenomenon to strong metabolic activity of the fibrocytes i e to an increase in quantity of the cellular products At the strengthened protein synthesis hydroxyproline would become incorporated and the formation of collagen precursor would increase in intracellular space

Immunology The chemical differences between the somatotropic hormones from different animal species are also evident in their biological effects when hormone of another species is administered Immunological studies reveal that protein hormones produce species specific antisubstances Owing to their effect the somatotropin preparations available at present have no effect on the rabbit and in the guinea pig they produce anaphylactic shock Man has also been found to become immune to somatotropin from steers (KOMER RANDLE and YOUNG 1959 HUNTER and GREEN WOOD 1962) The rat again is able to react to somatotropin preparations derived from a great variety of animals (LI 1960) It has not yet been clarified whether this is because the protein hormones of different species have a common biologically active nucleus (WILHELMI 1955) or whether the rat has an enzyme system which enables it to evaluate somatotropin obtained from various species (LI 1959)

2 42 *Thyrotropin*

Thyrotropin or thyrotropic hormone (TTH) is probably a secretion of the basophilic cells in the anterior pituitary lobe, the so called adeno hypophysis A water soluble substance it is difficult to isolate in the pure state (MORRIS and FAWCETT 1960) According to WILLIAMS (1955) thyrotropin is a protein hormone having a molecular weight slightly less than 10 000 and an isoelectric point in the range of 8 0—8 5

As the name implies thyrotropin exerts a thyroid stimulating effect but its direct influence on connective tissue has also been observed It becomes manifest in the generation of exophthalmus In currently available preparations two components can be distinguished the exophthalmus producing hormone (EPH) or ophthalmotropic hormone (OH) and the thyroid stimulating hormone (TSH) or thyrotropic hormone (BRUNISH 1960) They cannot yet be obtained free from each other The thyroxin hormone secreted by the thyroid gland has an inhibitory effect on hypophy seal thyrotropin secretion When thyrotropin is administered to intact experimental animals this regulatory mechanism causes inhibition of the thyrotropin effect

Metabolic effects IVERSEN and ASBOE-HANSEN (1952) found that thyro tropic hormone caused in guinea pigs hyperlipaemia and rapid transportation of fat from its normal places of storage to muscles, liver and kidneys A direct effect of thyrotropin is obviously concerned because thyroidectomy has no influence on the phenomenon (JEFFRIES 1949)

In human studies, SKANSE and VON STUDNITZ (1962) elicited no metabolic effect of thyrotropin in thyroidectomized patients The increase of basal metabolic rate and of erythrocyte sedimentation rate noted in their tests was attributed to the thyroid stimulating influence of thyrotropin The effect of thyrotropin on the normal organism was similar to the state encountered in infections This could also be observed by LAMBERG and GRASBECK (1955) in hyperthyroidism

Biological effects ASBOE HANSEN (1959) observed that on administration of thyrotropin the fat in the tissues is replaced by a mucinous substance which belongs to the acid mucopolysaccharides and is mainly hyaluronic acid LUDWIG BOAS and SOFFER (1959) found that mucopolysaccharides accumulate and hyaluronic acid increases in the retrobulbar tissue under the effect of thyrotropic hormone. The accumulation of water retaining hyaluronic acid in the said tissue probably increases the volume of the orbital tissue and causes exophthalmus (DOBYNS and STEELMAN 1953) The effect of thyrotropin is opposite to that of the glucocorticoid hormones in many respects

WEGELIUS and JOKINEN (1962) achieved with thyrotropin not only an increase in the quantity of mucopolysaccharides but also increased amount of connective tissue cells Stimulation of thyroid tissue but not of old mature connective tissue by thyrotropin *in vitro* was reported by BERGMARK HEIMAN and TENGROTEN (1964) Thyrotropin has also been found to exert an influence on the growth of cartilaginous tissue (THOMPSON and CREAN 1963) GYLLING (1964) produced with thyrotropin an increase in the relative ground substance quantity in connective tissue This phenomenon indicating immaturity of the connective tissue was highly distinct when thyrotropin was given together with somatotropin

Immunology FRIEGOOD (1934) observed that the metabolism accelerating effect of hypophyseal extract ceased in rats after four weeks and later administration of anterior pituitary extracts had no effect WERNER SEEGAL and OSSERMAN (1961) were in fact able to produce antiserum to thyrotropin from steers by hyperimmunizing rabbits A specific, precipitating antibody was then formed The antisera were able to neutralize the thyrotropin effect In man SKANSE and STUDNITZ (1962) have found the metabolic effect of thyrotropin extracts to vanish after two weeks hormone medication Hormone given after this period did no longer affect the metabolism

3 PROBLEMS

The facts reviewed in the preceding chapters reveal that the regeneration of tendons and the formation of adhesions in the course of the process are still rather incompletely known in many respects and that little actual knowledge exists concerning hormonal effects in this connection It seemed appropriate to undertake a study aiming at clarification of the manner in which adhesions are formed between a traumatized tendon and its surroundings under the effect of thyrotropin and somatotropin

In planning this study endeavours were made to enlist such methods of investigation the results of which can be expressed by numerical values and examined for mutual correlation This enables comparisons to be made between the results found by the different methods and the findings to be checked both empirically and mathematically On such reasoning the following quantities were chosen to constitute the objects of the present study tensile strength and elongation of the tendon adhesions cross section of the adhesions and data obtained by histological tissue analysis

On the basis of the foregoing the following questions were considered to require particular attention

(1) What effect is exerted by thyrotropin and somatotropin on the tensile strength and elongation of the adhesions formed around a traumatized tendon ?

(2) What is the effect of the said hormones on the cross section area of these adhesions ?

(3) What changes are caused by the said hormones in the histological picture presented by the granulation tissue developing around the tendon ?

(4) What correlations if any are demonstrable between the results yielded by the three methods of investigation mentioned ?

(5) Are the results obtained in answer to the questions examined here also applicable in general when other instances of formation of granulation tissue under hormonal effect are concerned ?

4 MATERIAL AND ARRANGEMENT OF THE WORK

4 1 Experimental animals, their selection and handling

For reasons of operation technique it is convenient to choose a large sized animal species to be used in experimental tendon studies HUECK (1923) MASON and ALLEN (1941) and CONZALES (1953) used for this purpose the dog which has large well developed and easily accessible tendons covered as they are by a thin subcutis In extensive series tests however it is difficult to assemble a material of uniform size and age of this animal species Studies of this kind have therefore been made, for instance with the cat (NARVI 1926) and rabbit (CARSTAM 1953 SKOOG 1954) whose extensor hallucis longus tendon seems to be well appropriate for the purpose in question

However since the present work involves the effect of protein hormones such as somatotropin and thyrotropin the rat was chosen as experimental animal in the study to be reported in the following The choice seems advisable in the light of previously presented immunological factors (LI 1960) Moreover adequate control references are available concerning experimental work carried out with the rat under the effect of the said hormones it does not concern the tendons but still the mesenchymal tissue (TRAUBENHAUS 1950 CAVALLERO 1953 SCOW 1951, SAIKKU 1956 KOSKINEN 1959)

In the handling of the experimental animals all known systemic factors of influence on the healing of wounds were taken into account as carefully as possible The experimental animals were young albino rats of equal age four months All belonged to the same Wistar strain Male rats were exclusively used their body weight varying between 210 and 320 g Only completely healthy animals in good condition were included in the tests They were kept in a draught free airy and dry room in natural light Electric light was only occasionally used The temperature in the room was maintained at a uniform 20 C Ten rats were accommodated in each cage and they were returned to the same familiar cage after the operation Care was taken of the animals protein mineral vitamin and fluid requirements by feeding them a commercially manufactured special diet (Hankkija s feed mixture for mice) and giving them fresh milk and water ad lib

4.2 Anatomical considerations

The tendon constituting the object in experimental tendon studies should be easily accessible and isolable from other tissues by operation In order to facilitate the operation, the tendon should be located close to the surface free from muscles and it should have uniform structure (GONZALES 1953) Even though the rat is a small animal its Achilles tendon was found to comply with these requirements With its length of only 2 cm it is comparatively short for complicated tendon operations but the length was found to be sufficient for the intended adhesion studies

The Achilles tendon located in the distal part of the lower leg on its posterior side lies in the rat under a nearly hairless or very short haired skin with scanty subcutis Medial to it lie the tibial nerve and posterior tibial artery which are easily separable from the tendon Immediately under the tendon the tibia and the ligamentous structures of both ankle joints are encountered The tendon itself consists of two bundles the gastrocnemius and soleus muscles which both attach to the calcaneus Although according to BUNNELL (1944) tendons possessing a peritenon chiefly occur only in places where the tendon has to make a bend, microscopic examinations revealed that the tendon has a peritenon and mesotenon close to the calcaneus It seems obvious that nutritional circumstances are decisive in this respect seeing that the movable skin covering the tendon carries few blood vessels at this particular point

4.3 Operating technique

The indispensability of most painstaking accuracy in performing the operation and in traumatizing the tendon has to be stressed The local factors affecting the healing of the wound have to be carefully taken into account in order to ensure highest possible uniformity of the trauma

Keeping these aspects in mind, traumatization of the Achilles tendon was effected in the following manner The animals which had been denied any food during eight hours prior to the operation, were anaesthetized with ether Both lower extremities were scrubbed with soap and water The skin was swabbed with alcohol and the animal was then placed on its stomach on a sterile support The operating area was covered with an operating cloth wetted with sodium chloride solution, in which small holes were made at the points of entry Since the skin was nearly hairless or carried very short hair where it was to be pierced it was not considered worth while to traumatize it by shaving the hairs

The operation was performed under strictly aseptic conditions using instruments sterilized in the autoclave An assistant held the anterior part of the animal s body with one hand and the extremity to be operated upon with the other bending it to a right angle at the ankle joint over the edge of the operating table Since no operating lamp with filter was available

merely indirect reflected light was employed The operation on the right lower extremity was invariably performed first Beside the Achilles tendon on its lateral side an incision 1 5 cm in length was made parallel to the tendon Due to the practice of following an atraumatic operating technique virtually no bleeding occurred The subcutaneous fascia and the peritenon were opened at an acute angle excercising care not to touch the tendon The peritenon was drawn aside at an obtuse angle to the medial side by which the tendon was exposed The tendon was lifted into view with a round smooth instrument

Traumatization was performed at a point 1 cm from the attachment of the tendon to the calcaneus The tendon was placed between the jaws of a clamp 5 mm in width and the clamp was tightened with the same amount of force in every instance This produced a flattening of the tendon so that distinct impressions could be seen in the epitenon on macroscopic examination (Fig 1) The tendon was then allowed to settle back in its proper position No attempt was made to close the peritenon The skin was sutured with five zero atraumatic silk stitches spaced at 3 mm and the wound was covered with a Nobecutan film

Exactly the same measures were then performed on the left Achilles tendon No expedients for draining blood from the wound or for haemostasis were necessary The entire surgical interference took only five minutes per extremity The animals were left to recover from the anaesthesia in individual boxes and were ultimately r turned to the previous cage housing their particular group Each operation series together with its controls was put through the operation on one and the same day

It should ne noted that the traumatizing of the tendon included no cutting of its fibres, nor was any kind of tendorrhaphy undertaken This was in the interest of highest possible uniformity of the trauma produced in each tendon It is not fully consistent with the trauma most commonly ocurring in operative tendon surgery In previous experimental tendon surgery the trauma has been made to consist of severing and resuturation of the tendon in cases in which prevention of the adhesion by means of interposition has been attempted (Henze and Mayer 1914 Wilmath 1937 Weckesser, Shaw, Spears and Shea 1949 McKee 1945, Wheeldon 1939 Stinchfield 1950 LeVeen and Barberia 1949 Gonzales 1949 and Ashley Stone Edwards and Sloan 1960)

The tendon was severed also by Wehner (1923), Hueck (1923) Narvi (1926) Mason and Allen (1941) Ashley Stone Edwards and Sloan (1960) and Potenza (1962) in their studies on the recovery mechanism of the tendon In his work concerning the adhesions that are formed around a tendon Carstam (1953) applied a traumatizing procedure in which the surface of the tendon was rubbed with a piece of dry gauze whereupon the tendon was squeezed at two points with artery clamps and finally one quater of the tendon s fibres were severed by incision at three points Mason and Allen (1941) concede, however, that already

damage to the epitenon of the tendon causes adhesions In SKOOG s (1954) studies injury of the epitenon was found to cause strong formation of adhesions and fibroblast invasion from the surrounding tissues into the tendon

Preliminary studies performed by the writer showed that mere contusion of the tendon and damage to its epitenon were sufficient to provoke the formation of adhesions More complex traumatizing procedures are accompanied by a great number of local factors influencing the healing of the wound such as tissue destruction risk of infection foreign body irritation haemorrhage cooling of tissues radiation etc each of which contributes in its own manner to the course of the healing process For this reason the traumatization described above is thought to be preferable while it is adequate and reliable at the same time

4 4 Experimental groups

Subsequent to operation the experimental animals were immediately divided into four groups



Fig 1 Traumatized tendon photographed during operation The impressions left in the epitenon by the clamp can be seen

(I) *Control Group* (subsequently referred to by the symbol C) The animals in this group were given an i m injection of 0 1 cc physiological saline into the muscles of the back immediately after the operation and thereafter once every day

(II) *Somatotropin Group* (STH) In this group an i m injection of 25 tibia units somatotropin (»Somacton» of Ferring Ab, Malmo, Sweden) into the muscles of the back was administered immediately upon operation and subsequently once every day

(III) *Thyrotropin Group* (TTH) In this group an i m injection of 0 1 U S P units thyrotropin (»Actyron» of Ferring Ab Malmo, Sweden) into the muscles of the back was administered immediately upon operation and later once every day

(IV) *Somatotropin Plus Thyrotropin Group* (STH + TTH) In this group the animals received simultaneous i m injections of 25 tibia units somatotropin and 0 1 U S P units thyrotropin into the muscles of the back immediately upon operation and subsequently once every day

Each group was subdivided into two subgroups The animals of the first subgroup were sacrificed after five days and those of the other after 14 days The sacrificing procedure was simple decapitation

The above mentioned sacrificing times had been fixed on the basis of considerations concerning the healing of the wound It was to be expected that the productive phase of the wound repair process would terminate at five days after the operation when the collagenous phase would begin (Dunphy and Udupa 1955 Edwards and Dunphy 1958) At 14 days the rate of the process in the collagenous phase of repair slows down considerably (Jackson 1958) Preliminary tests had also shown that five days and 14 days were the most appropriate times of examination

4.5 Statistical analysis

Presentation in detail of the methods of statistical mathematics employed in analysis of the results obtained in the present study is not thought to be indicated and reference to pertinent text books (e g Cramér 1946) may suffice It shall merely be mentioned that in applying Student s *t* test a highly significant significant or almost significant difference has been stated to exist when the probability for the deviation between two sets of values to be due to chance and not actually true was less than 0 001 (1 %) less than 0 01 (1 %) or less than 0 05 (5 %) respectively on the strength of the test.

5 TENSION TESTS

5 1 Procedures of tensile strength investigation

5 11 Characteristics of tensile strength and their investigation in physics and technology

The nature and structure of physical substances and also of organic tissues determine their physical properties Changes in structure among others are reflected as changes of the strength characteristics These are values describing the behaviour of the material when it is subjected to stresses produced e g by the action of external forces The principal modes of stress are tension compression shear bending and torsion stress concerning each of which specific theories have been elaborated Within each category a difference has to be made between static and dynamic stress The latter means that the direction of the force continuously alternates and failure under dynamic stress has mostly the character of a fatigue phenomenon

The forces to which a tendon attached to its enviroment by adhesions is subjected vary incessantly in direction A condition of dynamic stress would thus seem to be concerned From MASON and ALLEN s (1941) studies the inference can be drawn that the dynamic aspect is rather significant in practical surgery from the viewpoint of the development of adhesion tissue However experiments involving static load i e with constant direction of the acting force are much less elaborate than dynamic strength examinations and relevant conclusions concerning the behaviour of the subject can also be drawn from them

If a body or a piece of tissue is subjected to the action of an external force if it is placed under load the force tends to change the mutual positions of its particles or to detach them entirely from each other The amount of deformation is usually proportional to the magnitude of the force up to a given limit the elastic limit When this limit has been passed the deformation is no longer reversible In medical applications this can be

considered equivalent to the point at which traumatic effects are elicited the trauma limit.

The behaviour of a great number of materials under tension or compression is characterized by *Hooke's law* According to this law the elongation of a bar or wire under tensile load or its compression under compressive load λ, is proportional to the initial length, l to the magnitude of the deforming force, F, and to the inverse of the cross section A of the bar or wire. This is expressed by the equation

$$\lambda = \frac{F\,l}{E\,A}$$

where E is a characteristic constant of the material and is called its modulus of elasticity The quotient $F/A = \sigma$ is the stress acting at every cross section of the object under load When the load is increased to a certain limit, the yield limit, Hooke's law ceases to be valid the deformation increases without further increase of the load. Later, still the breaking limit is reached at which the specimen fails by rupture. The value of the stress at which this occurs σ is called the ultimate tensile or compressive strength of the material

In virtually all branches of technology strength tests are applied as routine in order to control the products compliance with specifications and in research. Changes of physical and chemical properties are rather sensitively reflected e g by the tensile strength value and for this reason tensile strength determinations are practised e g in the textile and paper industries as a means of controlling the uniformity of the output When the durability of yarns is tested, it is usual to determine the ultimate elongation in addition to the ultimate tensile strength by which a more complete picture is obtained of the yarn s properties

The tensile strength testing procedure suggests itself as a suitable expedient also when it is desired to observe the physiological and pathological changes occurring in organic tissues In such previous studies in which this has been done, the methods and equipment have mostly been borrowed from the textile or paper industry which have to deal with strength characteristics and dimensions roughly in the same order of magnitude. It seems appropriate to present a brief review of the equipment of the said kind employed in the above mentioned branches of technology

(1) A balance has been used, adding weights or a length of chain into one of its pans (Bowman Matthews rev by Skinkle 1949) or pouring water into it (Krais rev ibid.) The pan may also be pulled down by an electromagnet (Barratt rev ibid.) or the load increase may be achieved by allowing water to flow out of a cylinder (O Neil, rev ibid.) Devices of this kind are obsolete and they have been discarded owing to their inaccuracy and inconvenience and because they are slow in operation.

(2) In pendulum type testing machines a pendulum is deflected from its equilibrium position by means of a force applied through the yarn to be tested The ultimate strength is determined from the position of the pendulum at the moment when the yarn breaks The load is applied by turning a hand wheel by means of an electric motor or with the aid of a hydraulically controlled weight (H BAER rev ibid) Testing machines of this kind are rapid practical and robust They are manufactured in several sizes for various applications

(3) Independent of the manner in which the loading force is generated and controlled its magnitude can be ascertained on the basis of the change in electrical resistance a thin metal wire experiences under the load this change being proportional to the acting force (the so-called strain gauge principle)

(4) In another class of devices a constant weight is placed on a carriage on rails When the rails are slowly tilted the force tending to put the carriage in motion gradually increases The accuracy of devices of this kind is good owing to the fact that the length elongation and cross section area of the specimen have no influence on the magnitude of the acting force A great variety of tests can be carried out with one and the same machine in addition to which its capacity is variable within wide limits by using different weights However the testing procedure is comparatively slow The device has not come into general use in industry for this reason

(5) Ballistic devices in which a pendulum is made to break the yarn that is tested and the change in its amplitude of oscillation is observed.

§ 12 Previous tensile strength studies in medical research

In their studies concerning the factors affecting the healing of wounds, the following authorities have been among those who employed tension testing machines of the kinds described above SANDBLOM (1944) FINDLAY and HOWES (1950 1952) JACKSON (1954) SANDBLOM and MUREN (1954) DUNPHY ENGLEBERT and UDUPA (1955) SAIKKU (1956) ZEDERFELDT (1957) LUNDGREN MUREN and ZEDERFELDT (1959) SANDBERG and ZEDERFELDT (1959/60) and KULLANDER (1962) Tension tests with tendinous tissue in particular have been carried out by NICOLA (1934) CRONKITE (1935/36) GRAZ (1937) MASON and ALLEN (1941) CARSTAM (1953) GONZALES (1953) MOBERG and STENER (1953) and DAVIDSON (1956)

The writer s preliminary studies revealed however that tension testing machines of the types common in industrial use are not well suited for tissue studies Such machines are required to be rapid, sturdy and practical, and they have been designed for application in closely circumscribed tasks Pendulum devices in particular are impractical owing to their small capacity Even when used in their originally intended application they introduce an error of about 2 5 % owing to friction and inertia according

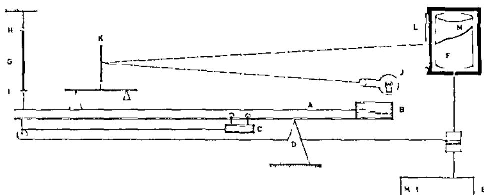


Fig 2 Principle diagram of the tension testing apparatus See text for detailed description

to SKINKLE (1949) Further errors are caused by the design of the clamping jaws, the length and the elongation of the test specimen The results are also affected by the rate at which the lower jaw moves and its uniformity Hand operated machines in particular are unreliable in this respect yielding rather arbitrary readings For the above mentioned reasons a special tensometer has been elaborated for use in the study of skin wounds (SANDBLOM, PETERSEN and MUREN 1953) The device is also suitable for clinical use but it is not quite as appropriate for the determination of the tensile strength of tendinous adhesions

3 13 Design and operation of the tension testing machine

The following characteristics are desirable in a tension testing machine to be applied in studying the tensile strength of organic tissues and particulary of tendon adhesions

- Minimum friction and inertia,
- Clamping jaws allowing no slipping yet producing no damage of the tissue
- Results to be unaffected by the length of the specimen
- Constant sensitivity with changing load,
- Possibility of changing the capacity of the device without change of sensitivity
- Automatic recording
- Determination of ultimate tensile strength as well as elongation shall be possible
- Elongation and load shall be determinable as each other s functions (i e the stres strain curve shall be obtainable)



Fig 3 Automatic tension testing apparatus specifically designed for the tension tests simultaneously recording the tensile force and the elongation of the specimen

With these aims in mind a device has been designed and built, the principle of which is shown by the diagram in Fig 2 In likeness with the previously mentioned devices employing a constant weight the device contains a weigh beam A supported at D so that it has two arms At one end the beam carries the counterweight B and the loaded carriage C slides on the beam The carriage is kept in uniform motion by the electric motor E which also rotates the recording drum F Each position of the carriage will thus be represented by a given vertical on the recording strip The tendon to be examined is placed between the clamps H and I of which H is adjustable in height The recording is accomplished by optical means A light beam emerging from a linear slit in front of the lamp J is reflected by the mirror K through a cylindrical lens L onto the light sensitive paper on the drum F on which a curve M is thus traced Any elongation of the specimen causes the position of the beam A to change and the light beam is reflected at a different angle from the mirror K The tracing will show a corresponding vertical displacement (Fig 3)

5 2 Behaviour of adhesions under effect of a static force

5 21 Method of investigation

The procedure in the tests for elucidation of the phenomena occurring when established tendon adhesions are subjected to a tension force was as follows

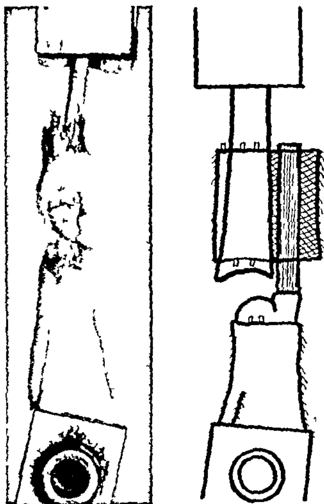


Fig 4 Lower extremity specimen placed in the tension testing apparatus The foot is attached to the lower leg only by the adhesions around the Achilles tendon. These circumstances are more clearly shown by the schematic diagram

A careful examination was made of the operation wounds of the animals operated traumatized and treated in previously stated manner (p 27) for the tension tests In some instances signs of infection were macroscopically observable the wound had opened and there was purulent secretion Such animals were excluded from the series

Immediately after the animals had been sacrificed, their both hind legs were amputated at a point close to the knee in the proximal part of the lower leg Exactly 1 5 cm from the point of attachment of the Achilles

tendon to the calcaneus, the skin and underlying tendon together with the soft tissues were severed and a transversal incision was made down to the bone All soft tissues proximal to this point were removed leaving only the tibia The talo-crural joint was exposed through an incision made on the anterior side of the ankle and continued around the calcaneus along a path distal to the point of attachment of the Achilles tendon The ligaments of the talo-crural joint, all tendons blood vessels and nerves passing over this point were cut In this manner the Achilles tendon alone remained as a connection between lower leg and foot On a length of 1 5 cm the Achilles tendon and the lower part of the tibia were surrounded by a *sleeve consisting of the skin and soft tissues which had been left intact* In the tension tests the tendon was then pulled out from this sleeve

For the test the end of the tibia fragment was fixed in the upper clamp of the apparatus which had been specially designed to admit the bone fragment In some instances the end of the fragment was crushed when the clamp was tightened resulting in loss of the specimen The lower clamp was applied around the foot The grip of the clamps was positive and no slip likely to introduce an error was observable (Fig 4)

Upon completion of the clamping operation, and after the weighted carriage of the apparatus had been brought into its zero position the tension testing apparatus was started In the course of the test the apparatus *produced automatically a record on photographic paper i e a curve* showing the relationship between stress (magnitude of the load) and strain (elongation)

5 22 Interpretation of the tension test record

The character of the curves obtained by the action of the automatic recording device in the tension tests shall be described in the following

The curve can be understood as a graph showing the force applied to the specimen and its elongation as functions of each other The distance along the horizontal axis corresponds to the magnitude of the force and the *distance along the vertical axis to the elongation* The graph has a general shape as shown in Fig 5

At the start of the test a small amount of yielding occurs while the tendon becomes taut After this, the graph ascends at a slope differing very little from the horizontal at low values of the elongation This part of the graph is linear, indicating that the elongation increased in proportion with the force So far Hooke s law of elasticity is completely valid in the test.

At the point consistent with a force F_1 equalling approximately one fourth of the ultimate tensile strength (F_3) abrupt yielding occurred, in the course of which the elongation increased from λ_1 to λ_2 with hardly any increase of the applied force. A sudden stop of the yielding signifies that the tendon has become completely detached from its adhesions to bone and ligaments After this point from the force F_2 onward, follows another linear portion of the graph, with proportional increments of elongation and force. At a certain force F_3, to which corresponds the elongation λ_3 the tendon at last comes free of the surrounding skin and soft tissues This value of the force is the tensile strength of the adhesions that have been established around the tendon, and λ_3 is the corresponding ultimate elongation.

Individual variations between specimens were noted in the value of F_1 and particularly in the amount of intermediate yielding $\lambda_2 - \lambda_1$ In some instances this yielding took place in two instalments Some preparations were lost from the viewpoint of the present study for the reason that the record started at a point too high up on the paper and the ultimate portion ran off the paper

For calibration of the tension testing apparatus one end of the weigh beam of an analytical balance was linked to the upper pecimen clamp and the balance was weighted in steps of 50 g The vertical scale of the graphs was calibrated in terms of elongation by shifting the position of the same clamp in steps of 1 mm with the aid of a micrometer screw and cathetometer The tracings obtained by this means on the recording paper showed both scales to be linear in terms of the respective quantity and the values read from the records are thus proportional to the actual force and elongation without any corrections. If the absolute values are desired, the F readings (in millimetres) have to be multiplied by 7 70 to obtain the force in grammes while the factor 0 1665 converts the λ readings (in millimetres) to the corresponding elongations in millimetres

5.3 Tension tests after 5 days

5 31 Experimental groups

The tension test series with specimens from animals sacrificed five days after the operation comprises 43 male rats The animals were four months old and their average weight was 230 g The operations by which their Achilles tendons were traumatized were performed by one and the same person in the previously described manner (p 27) The operations on all animals of the series were carried out at one session. Immediately upon completed operation the animals were divided into four groups as follows

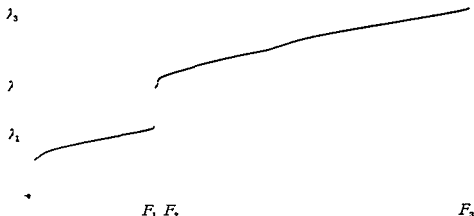


Fig 5 Record obtained in a test with the tension testing apparatus See text for detailed account

(I) Control Group (C) — 11 animals These animals received a daily injection of sodium chloride

(II) Somatotropin Group (STH) — 11 animals Daily injections of somatotropin were administered to these animals according to the schedule presented in the foregoing (p 30)

(III) Thyrotropin Group (TTH) — 10 animals Daily thyrotropin injections were administered in this group (see p 30)

(IV) Somatotropin Plu Thyrotropin Group (STH + TTH) — 11 animals The animals received a combined somatotropin and thyrotropin injection every day (see p 30)

All animals concerned here were sacrificed five days after the operation and specimens derived from their both Achilles tendons were subjected to the tension test

§ 32 Forces required to detach the adhesions

The recorded value F_1 represents the force at which the first yielding occurred when the tendon became detached from its bony and ligamentary adhesions As a rule this point on the graph was easy to determine accurately In the tests with some of the specimens the curve shows merely a slight angulation at this point

The recorded value F_2 corresponds to the force prevailing at the moment when the yielding of the specimen has come to an end This is the moment when the soft tissue adhesions come under tension Since the preceding

phase was one of yielding the F_2 values are little different from the respective F_1

The value F_3 indicates the force which is high enough to cause complete detachment of the tendon from its adhesions This point too, can be accurately determined because the recorded curve breaks off here In some instances this end point of the curve fell outside the recording paper and the specimens were consequently lost As can be seen from Figs 6 and 8 the F_3 value is roughly four times the corresponding F_1

Detachment from firm adhesions (F_1) The values in Fig 6 reveal that the forces required to detach the tendon from its adhesions to bone and ligaments five days after the operation are not significantly different in the various hormone treatment groups from those found for the controls nor mutually between the hormone treatment groups

Yielding (F_2) The yielding phenomenon after the first detachment of the tendon proceeds virtually without incremental force Consequently, the F_2 values are not essentially different from the F_1 values nor can any significant differences be noted between the different groups (Fig 7)

Tensile strength (F_3) The means stated in Fig 8 show that the force required to set the tendon entirely free from its adhesions has undergone the following changes in the different hormone treatment groups

— in the somatotropin group the strongest adhesions were noted after five days, and the force needed for their detachment was highest in this group,

— the force was next highest in the control group

— in the thyrotropin group a smaller force sufficed to liberate the tendon from its adhesions than in the control group

— in the somatotropin plus thyrotropin group the required force was smallest of all

Statistical study with the aid of Student s *t* test revealed significant differences between the groups as follows

The forces required in the STH + TTH group and in the TTH group are both smaller than that in the STH group at a highly significant level, and the difference by which the force in the STH + TTH group is smaller than in the C group is statistically significant No other significant differences exist between the groups

5 33 Elongations

The recorded value λ_1 represents the elongation at the moment when the tendon becomes detached from its firm adhesions In absolute values, the λ_1 elongations are in the order of 2 5 mm It is seen that a comparatively firm tissue is concerned

The recorded value λ_2 corresponds to elongation at termination of the yielding phase, subsequent to detachment of the bony and ligamentary adhesions This value can be determined with good accuracy since the direction of the curve changes quite abruptly at the point in question

The λ_3 value indicates the total elongation of the specimen immediately before the tendon is ultimately freed from its adhesions Constituting the terminal point of the curve, this value was easily determinable from the records

Detachment from firm adhesions (λ_1) The bony and ligamentary adhesions undergo only a small elongation prior to detachment The differences between groups are also quite small and no statistically significant differences between the hormone treatment groups mutually or between them and the control group could be noted (Fig 9)

Yielding (λ_2) The actual amount of yield is stated by the difference $\lambda_2 - \lambda_1$ It was noted in the foregoing that the λ_1 values are closely equal and instead of this difference we may therefore consider the λ_2 values The means stated in Fig 10 show that the elongation attendant on yielding of the tissue was smaller in the somatotropin group than in the control group, which was approximately equalled by the thyrotropin group in this respect. The greatest elongation was noted in the somatotropin plus thyrotropin group

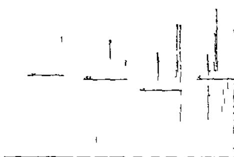
Ultimate elongation (λ_3) The elongation attained at the moment when the tendon became entirely free was smaller in the somatotropin group than in the control group while its order of magnitude in the thyrotropin group was the same as in the controls In the somatotropin plus thyrotropin group a higher ultimate elongation than in any other group was noted (Fig 11)



Group	Mean	S D	Var	Difference compared to
C	59	18	0 30	C
STH	47	16	0.33	STH
TTH	48	22	0 45	TTH
STH +TTH	56	23	0 39	

*** Statistically highly significant
** Statistically significant
* Statistically almost significant

Fig 6 Individual values (diagram on the left) and means (table on the right) of the force (F_1) required to detach the tendon from its firm adhesions after five days



Group	Mean	S D	Var	Difference compared to
C	62	18	0 30	C
STH	59	20	0 33	STH
TTH	50	22	0 44	TTH
STH +TTH	60	23	0 38	

* Statistically highly significant
** Statistically significant
* Statistically almost significant

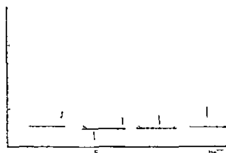
Fig 7 Magnitude of the force (F_2) after yielding has taken place after five days Individual values and means as in Fig 6 — F_2 is not greatly different from F_1 (Fig 6)



Group	Mean	S D	Var	Difference compared to
C	220	29	0 13	C
STH	233	26	0 11	STH
TTH	203	27	0 13	*** TTH
STH +TTH	194	21	0 11	** ***

*** Statistically highly significant
* Statistically significant
* Statistically almost significant

Fig 8 Ultimate tensile strength (F_3) of the tendon adhesions after five days shown as in Figs 6 and 7 but with smaller ordinate scale — The greatest force has been required in the STH group and the smallest force in the STH+TTH group The statistically significant differences between groups found on analysis have been indicated at the intersections of horizontals and verticals in the table



Group	Mean	S D	Var	Difference, compared to
C	16	5	0.32	C
STH	14	5	0.35	STH
TTH	15	5	0.34	TTH
STH +TTH	16	5	0.32	

*** Statistically highly significant
Statistically significant
* Statistically almost significant

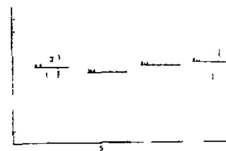
Fig 9 Elongation under the force detaching the tendon from its firm adhesions (λ_1) after five days. No great differences between groups are observed.



Group	Mean	S D	Var	Difference compared to
C	28	10	0.35	C
STH	23	9	0.39	STH
TTH	26	10	0.39	TTH
STH +TTH	35	14	0.40	

Statistically highly significant
Statistically significant
Statistically almost significant

Fig 10 Elongation after yielding has taken place (λ_2) after five days. The smallest elongation was obtained in the STH group



Group	Mean	S D	Var	Difference compared to
C	62	10	0.17	C
STH	57	8	0.13	STH
TTH	62	7	0.11	TTH
STH +TTH	65	11	0.17	

Statistically highly significant
* Statistically significant
* Statistically almost significant

Fig 11 Elongation under a force equivalent to ultimate tensile strength (λ_3) after five days. No statistically significant differences between groups

5 4 Tension tests after 14 days

5 41 Experimental groups

The tension test series with specimens derived from animals sacrificed 14 days after the operation comprises 41 male rats of four months age Despite their equal age, the animals varied in weight between 210 and 320 g the average weight was 255 g The Achilles tendons of the rats were traumatized in the manner described before (p 27) One and the same person performed all operations at one session The animals were divided into the following four groups immediately upon operation, each group being placed in its particular cage

(I) Control Group (C) — 10 animals The animals of this group were given daily injections of sodium chloride

(II) Somatotropin Group (STH) — 10 animals Daily injections of somatotropin (see p 30) were administered in this group

(III) Thyrotropin Group (TTH) — 10 animals The animals received daily injections of thyrotropin (see p 30)

(IV) Somatotropin Plus Thyrotropin Group (STH + TTH) — 11 animals Combined somatotropin and thyrotropin injection was administered once every day (see p 30)

The rats were sacrificed 14 days after the operation and their Achilles tendons were detached from their adhesions in the tension testing apparatus

5 42 Forces required to detach the adhesions

As in the test series with animals sacrified five days after the operation, the recorded value F_1 represents the force which is able to detach the tendon from its bony and ligamentary adhesions The yielding subsequent to this detachment came to an intermediate stop in some specimens, starting again after a slight increase of the force Two values were obtained in these instances for F_1

On the basis of the point at which the interrupted graph resumes its uniform course, the force F_2 prevailing at the end of the yielding phase can be determined The yielding of one specimen from the control group took place in two stages

The reading F_3 consistent with the terminal point of the recorded curve gives the force at which the tendon was completely detached from its adhesions The automatic operation and recording of the tension testing

apparatus and its design ensure that the accuracy of these readings is equally good as that of the values found in tests with smaller load

Detachment from firm adhesions (F_1) The values seen in Fig 12 display considerable scattering There are no statistically significant differences between the hormone treatment groups mutually or between them and the control group

Yielding (F_2) In likeness with the values of the force considered just before (F_1) the F_2 values are scattered over a fairly wide range. The increase of the force from F_1 to F is insignificant, and no statistical analysis was thought to be worth while in respect of these observations (Fig 13)

Ultimate tensile strength (F_3) The forces causing ultimate liberation of the tendon in the series referring to 14 days hormone treatment (Fig 14) are clearly different in the different groups namely

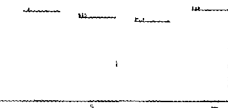
- in the somatotropin plus thyrotropin group the highest force was required to effect complete detachment
- the force needed in the thyrotropin group was smaller, but it was distinctly superior to those in the other two groups
- the next highest force was recorded in the control group
- in the somatotropin group the tendon became completely detached with the smallest force

According to statistical analysis by Student s t test *the superiority of the force in the STH + TTH group over those in the C and STH groups is highly significant and the difference against the TTH group is statistically significant The force in the latter group is also higher than that in the STH group at a statistically significant level* No other statistically significant differences with respect to the controls exist than that stated above

5 43 Elongations

The λ_1 elongation corresponding to the moment of detachment from the firm adhesions consisted of two components in the case of three control specimens because the yielding ceased and continued again after some increase of the force

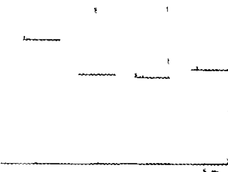
The elongation λ_2 at the end of the yielding phase was mostly easy to determine except for one control specimen in which another yielding phase ensued



Group	Mean	S D	Var	Difference compared to C	STH	TTH
C	68	34	0 51			
STH	63	26	0 42			
TTH	60	26	0 43			
STH + TTH	69	18	0 25			

** Statistically highly significant
* Statistically significant
* Statistically almost significant

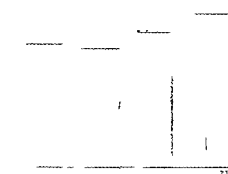
Fig 12 Forces (F_1) required to detach the tendon from its firm adhesions after 14 days No significant differences between groups



Group	Mean	S D	Var	Difference compared to C	STH	TTH
C	93	30	0.32			
STH	68	26	0 38			
TTH	65	29	0 44			
STH + TTH	72	19	0 26			

* * Statistically highly significant
** Statistically significant
* Statistically almost significant

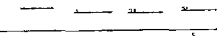
Fig 13 Magnitude of the force (F_2) after yielding has taken place after 14 days



Group	Mean	S D	Var	Difference compared to C	STH	TTH
C	249	29	0 12			
STH	240	29	0 12			
TTH	273	20	0 07		**	
STH + TTH	309	41	0 13	***	*	*

* Statistically highly significant
* Statistically significant
* Statistically almost significant

F g 14 Ultimate tensile strength (F_3) of the tendon adhesions after 14 days smaller ordinate scale than in Figs 12 and 13 Statistically significant differences between groups are noted In contrast to the results recorded after five days the highest force has been required to detach the adhesions in the STH + TTH group and the smallest force in the STH group



Group	Mean	S D	Var	Difference compared to
C	18	6	0.33	C
STH	14	3	0 23	STH
TTH	14	5	0.36	TTH
STH +TTH	15	5	0 33	

* Statistically highly significant
Statistically significant
Statistically almost significant

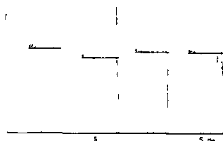
Fig 15 Elongation (λ_1) under the force detaching the tendon from its firm adhesions after 14 days



Group	Mean	S D	Var	Difference compared to
C	35	12	0 37	C
STH	26	13	0 49	STH
TTH	31	13	0 43	TTH
STH +TTH	29	12	0 41	

* Statistically highly significant
** Statistically significant
Statistically almost significant

Fig 16 Elongation after yielding has taken place (λ_2) aft r 14 days



Group	Mean	S D	Var	Difference compared to
C	68	9	0 13	C
STH	61	13	0 21	STH
TTH	65	7	0 10	TTH
STH +TTH	64	11	0 17	

Statistically highly significant
** Statistically significant
* Statistically almost significant

Fig 17 Elongation under a force equivalent to ultimate tensile strength (λ_3) after 14 days

No difficulties were encountered in determining the ultimate elongation λ_3 except in a few instances in which the curve extended past the upper edge of the recording chart

Detachment from firm adhesions (λ_1) The values found for λ_1 are not essentially different in the hormone treatment groups mutually, nor from the value in the control group No statistically significant differences can be expected to exist (Fig 15)

Yielding (λ_2) The smallest amount of yielding is noted to have taken place in the somatotropin group The other groups are little different from the control group in this respect (Fig 16)

Ultimate elongation (λ_3) The ultimate values reached by the elongation at the moment of complete detachment of the tendon are not essentially different between the hormone treatment groups nor between these and the control group The smallest value was found for the somatotropin group but there is no statistically significant difference in comparison with the controls (Fig 17)

5 5 Comparison of results after 5 and 14 days

5 51 Forces required to detach the adhesions

Detachment from firm adhesions (F_1) Comparison of the F_1 values found as means for the different groups five days and 14 days after the operation reveals that the force required to detach the tendon from its

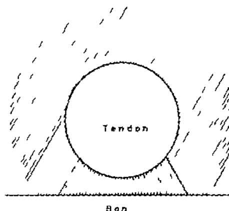


Fig 18 Schematic diagram illustrating the fact that only a small part of the adhesions formed around the tendon attach the tendon to the underlying bone

bony and ligamental adhesions increased in all groups during the intervening period The graphical plot representing this change is a line of very nearly identical slope in each group, indicating that the increase is proportionally the same in all hormone treatment groups as well as in the control group *The increment is quite small, though in all groups It is* to be concluded that hormone treatment has no effect on it (Fig 19)

Referring to the schematic drawing presented in Fig 18, it can be conjectured that there is only space for a small quantity of granulation tissue to be formed around the tendon on its side close to the bone The bone would thus act in the manner of an interposition preventing the formation of adhesions Owing to this mechanical inhibition of the proliferation of granulation tissue the effect of time and of hormonal factors does not manifest itself

Yielding (F_2) Since the yielding phenomenon requires virtually no incremental force the five day and 14-day F_2 values are not greatly different either nor are there any statiscally significant differences (Fig 20)

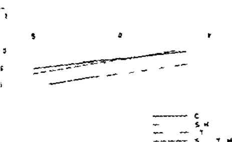
Ultimate tensile strength (F_3) More interesting observations are made on comparison of the forces needed to liberate the tendon entirely from its adhesions

In the series of animals sacrificed five days after the operation the highest force was required in the STH group to detach the tendon The control group was next followed by the TTH group and the force was least in the STH + TTH group In the 14-day series the sequence of the different test groups is exactly inverted the required force is highest in the STH + TTH group next highest in the TTH group and after that in the control group while the least amount of force was needed in the STH group

The graphical plots of the values in question reveal that the smaller the force required at five days after the operation the greater is the slope at which the graph rises towards the value at 14 days The increase is thus rather minimal in the STH group but highly marked in the STH + TTH group All four lines intersect each other, forming a fairly regular fan (Fig 21)

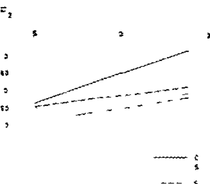
Analysis with the aid of Student s *t* test shows that statistically significant changes have ocurred in the ultimate tensile strength between five and 14 days after the operation

The increase of ultimate tensile strength from five to 14 days is statistically highly significant in the STH + TTH ard TTH groups and significant in the C group, whereas no statistically significant change is noted in the STH group



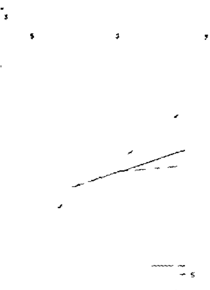
F_1	Group			
	C	STH	TTH	STH +TTH
5 days	59	47	48	56
14 days	68	63	60	69
Change	9	16	12	13

Fig 19 Comparison of the forces (F_1) required to detach the tendon from its firm adhesions after 5 and 14 days. No great differences are observed between groups



F_2	Group			
	C	STH	TTH	STH +TTH
5 days	62	59	50	60
14 days	93	68	65	72
Change	31	9	15	12

Fig 20 Comparison of the forces recorded after yielding has taken place (F_2) after 5 and 14 days The values are little different from those presented in Fig 19



F_3	Group			
	C	STH	TTH	STH +TTH
5 days	220	233	203	194
14 days	249	240	273	309
Change	29**	7	70***	115***

Fig 21 Comparison of the ultimate tensile strengths (F_3) after 5 and 14 days revealing statistically highly significant increase of the force in the STH + TTH and TTH groups and no significant increase in the STH group

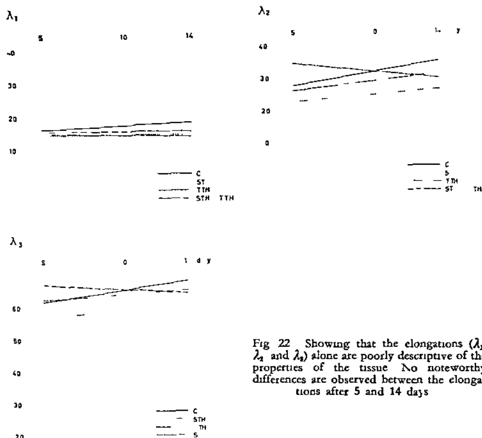


Fig 22 Showing that the elongations (λ_1 λ_2 and λ_3) alone are poorly descriptive of the properties of the tissue No noteworthy differences are observed between the elongations after 5 and 14 days

Group	λ_1		λ_2		λ_3	
	5 days	14 days	5 days	14 days	5 days	14 days
C	16	18	28	35	62	68
STH	14	14	23	26	57	61
TTH	15	14	26	31	62	65
STH +TTH	16	15	34	29	65	64

No statistically significant changes

5 52 Elongations

Comparison of the elongations at detachment of the firm adhesions, after yielding of the tendon and at the moment of ultimate liberation (λ_1 λ_2 and λ_3 respectively) yields no interesting observations, nor are the mutual magnitudes of their five day and 14-day values such that statistical study of the differences would be worth while As regards the adhesions between tendon and bone this is thought to be due to the progressive character of the adhesion formation At the yielding stage no additional energy is needed and therefore no differences in the structure of the tissue are elicited by the results The elongation alone is only one of the quantities involved in the relationship implied by Hooke s law and it is a poorly relevant one from the viewpoint of the physical properties of the substance which are of interest in this study (Fig 22)

5 6 Relationship of elongation and force

In Fig 23 the pairs of mutually consistent λ and F values found as means for the different test groups and referring to five and 14 days after the operation respectively, have been plotted and joined by broken lines producing a schematic approximation of the curve characterizing the relationship between elongation and tensile force in each instance

The diagram containing the graphs constructed in this manner to illustrate conditions at five days reveals that the graph of the STH + TTH group mostly runs on a higher level than all others and stops after a shorter horizontal course The STH graph is lowest in its relevant portion and covers the longest horizontal distance In the first mentioned group the elongation is highest and the ultimate tensile strength is lowest, and the opposite is true for the latter Among the graphs reflecting the behaviour at 14 days that of the STH + TTH group is lowest in position and extends farthest horizontally that is the elongation is smallest and the ultimate tensile strength is highest in this group

More lucid and informative comparisons can be made if a given fixed value is chosen for one of the two variables and the corresponding values of the other variable in the different instances are studied Thus we may choose for the elongation the fixed value $\lambda = 50$ (corresponding to 8 33 mm actual elongation) which has been indicated in Fig 23 The corresponding approximate F values will then be those stated in Table 3 on p 92

5 days

C	————
STH	- - -
TTH	— — —
STH TTH	—·—·—

14 days

C	————
STH	- - -
TTH	— — —
STH TTH	—·—·—

Fig. 23 Schematic force vs. elongation diagrams derived from the means of the forces (F_1, F_2 and F_3) and of the corresponding elongations (λ_1, λ_2 and λ_3) referring to tests after 5 and 14 days After five days the graph of the STH + TTH group is shortest and runs at highest level while according to the tests after 14 days the graph of the same group is longest and lower than any other graph.

If Hooke s law $\lambda = Fl/EA$ or $F = EA\lambda/l$ is formally applied with the figures just considered three of the variables involved, namely λ, l and F are given. The length of the adhesions $l = 5$ mm was determined by the traumatizing procedure, λ was fixed at a value equivalent to 8.33 mm, and F was read from the graphs For constant A, the force F is then seen to be proportional to the modulus of elasticity E which is a characteristic determined by the structure of the tissue subjected to tension E is greater

accordingly as the tissue is more compact and resistant to tension The symbol A stands for the cross section area of the adhesions If the values of A are separately determined, E can be calculated in each instance and inferences may be drawn from its value concerning the structure of the granulation tissue that has been formed.

5 7 Comments

It has been shown that traumatizing interference with the surface of the tendon, consisting of its compression without cutting any fibres of the tendon was sufficient to provoke formation of adhesions It is to be concluded that care should be taken in clinical work not to touch the tendon with angular hard instruments (cf BUNNELL 1921, LITTLER 1947 MASON 1955 ALLEN 1955 VERDAN 1951)

In the present study the surface of the tendon and the surrounding tissue were subjected to trauma. Since adhesions could be produced in this manner, the theories and studies are corroborated according to which the healing of a tendon takes place by proliferation of external connective tissue (WEHNER 1923 HUECK 1923 NARVI 1926, SKOOG and PERSSON 1954, DAVIDSSON 1956, ASHLEY et al 1960 POTENZA 1962)

The extremity was not immobilized subsequent to the operation, but this did not prevent adhesions from being formed Irritation due to movement has been found to increase the reaction at the traumatized point and the adhesion formation (MASON and ALLEN 1941) This refers to the first two weeks which is a period identical with the time covered by the present experiments

Numerous clinical details are seen to be involved even though the best attempt was made to render the requisite tendon trauma in the experiments as uniform as possible in every case. Compression trauma of the kind described here is one of the commonest clinical tendon lesions It is surprising that in spite of this fact exact experimental studies concerning this question are few in comparison with the ample clinical literature

In view of the circumstance that the formation of adhesions on the side of the tendon against the bone is largely inhibited, the finding is readily understandable that there are no considerable differences between the different treatment groups in the magnitude of the force required to detach the *firm adhesions* For the same reason the said force is not greatly different in the series referring to 5 days and 14 days after the trauma. Indications to the same effect can be derived from the behaviour of the elongation in the different test groups in both series At all events the

slightly higher values at 14 days suggest the presence of a progressive process

The *yielding* takes place without necessity of incremental force The highest yield in the five day series was noted in the STH + TTH group This suggests that the granulation tissue may have been of looser structure in this group than in the other instances The point shall not be discussed here since obviously additional evidence is needed The differences tend to level out towards the time of 14 days which might be taken as an indication of homogenization ocurring in the structure of the tissues in the different groups Such an assumption is well consistent with existing experience concerning the manner of healing of wounds and the general mode of action of hormones (DUNPHY ENGLEBERT and UDUPA 1955 JACKSON 1958 WILLIAMS 1955)

For the *ultimate tensile strength* the highest value in the five-day series was observed in the STH group with a statistically highly significant difference against the STH + TTH and TTH groups The same result has been reported by SAIKKU (1956) in his tension tests with cutaneous scars of the rat although no statistically significant differences were elicited in his studies The findings are in support of LI's (1960) statement that the rat is able to respond to somatotropin from a foreign species In respect of the cause responsible for the changes in tensile strength of the granulation tissue produced under hormonal influence reference can be made to the studies of AMROMIN (1950) and CAVALLERO (1953) who found that somatotropin stimulated the growth of granulation tissue

Paradoxically the highest ultimate tensile strength in the 14-day series was encountered in the STH + TTH group which differed at a statistically highly significant level from the STH and C groups in this respect. The question naturally arises why the STH group should present the highest tensile strength at five days and the lowest at 14 days and why the opposite is true for the STH + TTH group This must be connected with changes in the quality or quantity of adhesion tissue. Changes in quality are suggested by SCOW s (1951) studies and changes in the quantity of granulation tissue by those of TAUBENHAUS (1950)

Further light is thrown on this question by comparison of the five-day and 14-day tensile strengths in the different groups It is seen that in the STH group no worthwhile change takes place during this time It would seem that granulation tissue under the effect of somatotropin loses its proliferative ability at an earlier stage than that in the controls In the STH + TTH and TTH groups the differences between the five day

and 14-day values are statistically highly significant and it is concluded that a lively process must have been in progress (cf EDWARDS and DUNPHY 1958) Indications to the same effect are furnished by the elongation values

5 8 Synopsis of the tension tests

1 In the tension tests the recorded curve representing the relationship between elongation and tensile force was found to be composed of three parts, which correspond to the following phases detachment of the firm adhesions yielding and detachment of the soft tissue adhesions *The force required to overcome the adhesions to soft tissues was about four times that needed to detach the firm adhesions*

2 The administration of hormones had no effect on the tensile strength consistent with detachment of the firm adhesions in either test series (after 5 days and after 14 days)

3 The hormones exerted no noteworthy effect on the amount of yielding in either test series

4 No great differences between the groups with different hormonal treatment were elicited in respect of elongation in either test series

5 a) *The ultimate tensile strength at the end of the productive phase (after 5 days) was highest in the somatotropin group, with the other groups following in the order control, thyrotropin and somatotropin plus thyrotropin group Statistically highly significant differences were observed between the STH group on one hand and the TTH and STH + TTH groups on the other hand, and between the control and STH + TTH groups*

b) *The ultimate tensile strength in the collagen phase (after 14 days) was highest with combined somatotropin and thyrotropin treatment this group was followed by the thyrotropin, control and somatotropin groups, in this order Statistically highly significant differences existed between the STH + TTH group on one hand and the control and STH groups on the other hand, while the differences between the TTH group on one hand and the STH + TTH and STH groups on the other hand were statistically significant*

6 *Comparison of the results obtained in the test series carried out after 5 days and after 14 days revealed the greatest increase in ultimate tensile strength in the somatotropin plus thyrotropin group, the difference between the values relating to 5 days and 14 days being statistically highly significant, as was the difference by which the ultimate tensile strength increased from 5 to 14 days in the thyrotropin group The value increased during this period also in the control and somatotropin groups, the increment in the first mentioned group amounting to a statistically significant difference*

6 PLANIMETRIC STUDIES

6 1 Assessment of granulation tissue quantity

6 11 Quantitative methods

The commonest method employed in studying the effect of various factors on tissues is the gravimetric method Changes of weight may result from change of the absolute tissue quantity but also from that of its physical chemical properties e g of the fluid content

Simplicity is an advantage of the gravimetric method when a separate easily detachable organ is concerned Considerable difficulties are en countered on the other hand if for instance the factors affecting the amount of granulation tissue are to be investigated in this manner It is then necessary to apply a special technique in order to separate the generated granulation tissue from adjacent tissues SELYE (1953) developed a special so-called granulation pocket method for this purpose More generally used is the cotton knot embedded as suggested by STEBBINS and STOERK (1954) as a foreign body among the tissues to cause irritation resulting in formation of granulation tissue. VILJANTO and KULONEN (1962) used a piece of cellulose sponge to the same end

Granulation tissue produced by foreign body irritation acquires a specific structure characterized by giant cells No such cells could be observed in the granulations formed about a tendon Gravimetric methods could not be used with success in studying the adhesions formed around tendons

Easy distinction of the granulation tissue formed around an injured tendon is only possible by histological means Most of the histoquantitative methods are accordingly based on measurement of the intensity at which a given radiation is transmitted by the microscopic preparation or of the change in wavelength occurring at transmission The determinations are usually relative and refer only to a given part of the microscopic prep aration. It may suffice to mention briefly some of the methods based on this principle

The absorption of light outside the visible spectrum when it penetrates the microscopic preparation may be determined (BARER 1950) Microradiography may be used to determine the absorption of very soft x rays the absorption has been found to depend on the dry mass of the tissue (ENGSTROM and LINDSTROM 1950) The electron microscope may also be used in identical manner (SCOTT 1943) The property of autofluorescence of tissues is applicable in some instances (PRINGSHEIM 1949) Phase contrast and interference microscopes provide opportunities for quantitative refractometry (BARER, ROSS and TKACZYK 1953) ERÄNKÖ (1955) has presented several photometric methods in his book.

6 12 *Planimetric methods*

The force and elongation were studied in the preceding chapter in respect of their mutual relationship Such investigations are most naturally complemented by data on *cross section area* Considering the adhesions around a traumatized tendon in particular, their cross section area can be determined by planimetric methods The specimen is destroyed in the tension test involved in the above mentioned, preceding study and the preparations for planimetric study cannot be made from the same individual specimens unfortunately

Determination of areas with a grid When the eye piece of the microscope has a grid composed of small squares the size of a given area can be found by immediate counting of the whole squares it covers and estimation of the parts of squares cut by its boundary The same method of assessment can also be applied if an image of the preparation is projected on a screen divided into squares

Determination of areas with the planimeter Planimeters are mechanical devices operating on a mathematical principle and giving direct readings which represent the area of a plane figure with quite high accuracy It is particularly advantageous to use a planimeter when various parts of one and the same figure have to be measured The planimeter then also gives their aggregate area without need of addition

Determination of areas by planimetric weighing In determining the areas of simple large figures such as those concerned when the cross section areas of adhesions around a tendon have to be assessed the method of planimetric weighing has proved to be most appropriate It means

that an image of the preparation is projected on a sheet of homogeneous paper of uniform thickness, after which the boundaries of the area to be determined are traced on the paper, a corresponding piece is cut out and its weight is determined with an analytical balance All cut outs representing samples of one and the same experimental series may be weighed in aggregate and the result divided by the number of preparations to find the mean value with great accuracy The planimetric weighing method is widely used in quantitative histology TALA (1952) may be mentioned among those who have employed it

The range of auxiliary techniques employed in aid of planimetry may be enlarged to include quantitative histochemistry and medical chemistry but it does not seem appropriate to review the numerous possibilities which then present themselves

6 2 Experimental animals and groups

The principles outlined in the foregoing (p 26) were observed in selecting and treating the experimental animals which were male white Wistar rats in all experiments concerned here The entire material comprised 222 animals All endeavours were made to render the conditions and the care of the experimental animals equal to those in the preceding test series in order that all systematic factors affecting the wound healing might be excluded

The operative interference and traumatization of the rats tendons were carried out as described previously (p 27) This procedure for traumatization of the rat s Achilles tendon had already proved adequate, and the method was best conducive to uniformity of the local factors influencing the healing process

Likewise the postoperative treatment of the material took place in accordance with the previously described principles the experimental animals being immediately divided into four groups here, too The groups were thus

(I) Control Goup (C) — 63 animals altogether,
(II) Somatotropin Group (STH) — 51 animals altogether
(III) Thyrotropin Group (TTH) — 53 animals altogether
(IV) Somatotropin Plus Thyrotropin Group (STH + TTH) — 55 animals altogether

The medication applied in each group was the same as described on p 30 Each group was subdivided into two subgroups, the animals of which were sacrified five days and 14 days after the operation, respectively

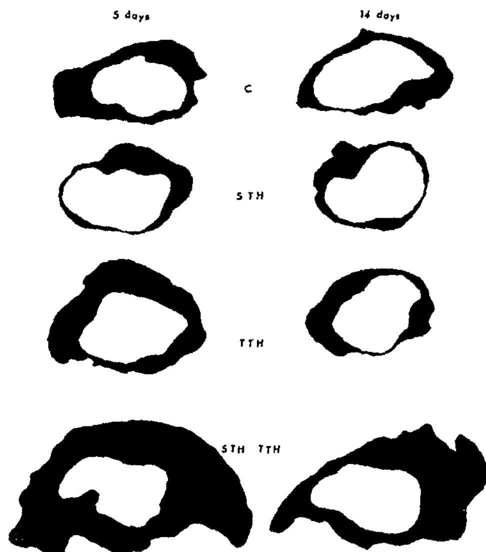


Fig 25 Example showing adhesion cross sections found in the different test groups after 5 and 14 days The areas are smallest in the STH group and largest in the STH + TTH group with synergistic action of both hormones after five days as well as after 14 days

paper manufactured by the mill Kankaan Paperitehdas was used The paper was made on special order without water mark and had a weight of 60 g per m, the manufacturers guaranteeing its weight differences not to exceed 4 %

The granulation tissue was organized around the tendons in such manner that there was a very thin course on the surface against the bone whereas

the thickest granulation layer was found on the surface against the skin, where the scar after the operation was located The conditions are illustrated by the schematic diagram in Fig 25 and by Figs 26—27

The areas to be determined were cut out from the paper sheets and weighed with an analytical balance providing an accuracy of 0 1 mg which was found to be sufficient All weighings were performed at one time at a given temperature and relative humidity of the air in order to exclude any effects that might be caused by varying moisture content of the paper

The results of the weighings in mg are relative values representing the cross section areas In the following they shall be stated and used as such When desired the true area of each cross section in mm² is found by multiplying the relative value by 0 00474 This conversion factor was determined from the average weight of ten separate paper cut-outs obtained in the same manner when the microscopic preparation had been replaced by a Burker counting cell with one tenth-millimetre grating each cut-out corresponding to 1 mm²

The data yielded by the described modified planimetric procedure can be brought into relationship with the results of the tension tests on the theoretical basis that the ultimate force required to rupture a homogeneous specimen equals the product of its tensile strength and its cross section area

6 4 Planimetric studies after 5 days

6.41 Experimental groups

The material was the same as that used in the tissue analysis (p 76) Since however only completely undamaged preparations could be sub jected to the planimetric procedure part of the preparations included in the tissue analyses had to be discarded here

The part of the material concerning animals sacrificed five days after the operation comprises altogether 117 rats The operative treatment medication and methods of investigation were the same as described in the foregoing (pp 27 30) As before the animals were divided into four groups

(I) Control Group (C) — 33 animals
(II) Somatotropin Group (STH) — 28 animals
(III) Thyrotropin Group (TTH) — 27 animals
(IV) Somatotropin Plus Thyrotropin Group (STH + TTH) — 29 animals



— Control group (C)



— STH group There is little granulation tissue around the tendon but in the original cut it is clearly distinct owing to its intense red staining



— TTH group A great amount of granulation tiss e of loose appearance has been produced.



— STH + TTH group (synergistic action of the hormones) The extraordinarily massive granulation formation threatens to rupture the scar

Fig ..6 Cross sections of Achilles tendons after five days. The tendon and its adhesions ar seen at the top At the bottom the skin is open after removal of the bone The scar after the operation can be seen in the upper right corner



– Control group (C)



– STH group The adhesions are small in area



– TTH group The traumatization did not extend to the boundary surface between the different parts of the tendon the epitenon is therefore untraumatized at this point and no adhesions have formed



– STH + TTH group (synergistic action of the hormones) It can be seen that the huge amount of granulation tissue is not limited to the area around the tendon the scar of the skin is also notably thickened.

Fig 27 Cross sections of Achilles tendons after 14 days The skin has healed and collagen is seen in ample amount in all instances

Although both extremities could not be included in the study in the case of all animals owing to the above mentioned causes the entire usable material was evaluated without exercising any selection The series are therefore comparatively extensive which is advantageous in the interest of reliable results

6.42 Cross section area of tissue components

The results obtained on planimetric study with the animals sacrificed five days after the operation can be found in Table 1 and are also shown by the graphs in Fig 28 separately for each of the four above mentioned groups The numerical values refer to the weights of the paper cut outs in mg (cf p 59) which are mutually comparable

The results reveal that the smallest cross section area of the granulation formed about the tendon occurred in the STH group Next in order of magnitude follow the C and TTH groups The granulation area was largest in the STH + TTH group that is with the animals which had been given combined somatotropin and thyrotropin treatment

Statistical analysis by Student s *t* test applied to the different groups in all possible combinations of two, revealed *statistically highly significant differences between all groups except between the C and TTH groups*

The observation can thus be made that combined somatotropin and thyrotropin medication produced substantially superior adhesions as regards their cross section area No conclusive difference is seen between the control and thyrotropin groups, but both are distinctly inferior to the STH + TTH group In the somatotropin group the adhesion cross section was smallest of all and it was clearly less than in any other group

6 5 Planimetric studies after 14 days

6 51 Experimental groups

The planimetric studies on specimens derived from rats sacrificed 14 days after the operation cover a material of altogether 105 rats The operative treatment medication and methods of investigation have been described in the foregoing (pp 27 30) The same material with some further animals added is also concerned in the subsequently reported tissue analysis studies (cf p 63) The results to be stated below therefore lend themselves to comparisons with the histological findings (p 76)

Table 1 Comparison of adhesion cross section areas found after 5 and 14 days in the different groups by planimetric study Statistically significant differences between groups and significant changes from 5 to 14 days are noted (Levels of statistical significance indicated for differences between groups at the intersections of horizontals and verticals in the table for changes from 5 to 14 days in the squares on the central diagonal)

5 days: Var	S D	Mean	Group	↑ C	STH ↓ / ↑ STH	TTH ↓ / ↑ TTH	STH +TTH ↓	Group	Mean	S D	Var: 14 days
0 25	104	414	C	**	*		***	C	324	86	0 27
0 32	98	303	STH	***		*	***	STH	276	87	0 32
0 31	144	465	TTH	*	***	***	***	TTH	328	80	0 24
0 23	188	817	STH +TTH	*	***	***	**	STH +TTH	654	229	0.35

Column headings as printed: top left "Var | S D | Mean | Group"; top right "STH TTH STH+TTH ↓ Difference compared to"; bottom left "Difference compared to ↑ C STH TTH"; bottom right "Group | Mean | S D | Var".

Squares on diagonal between both halves of the table Difference 5 days – 14 days

Unit mg of paper cut-out weight

*** Statistically highly significant
** Statistically significant
* Statistically almost significant

As before four groups of experimental animals have been considered

(I) Control Group (C) — 30 animals
(II) Somatotropin Group (STH) — 23 animals
(III) Thyrotropin Group (TTH) — 26 animals
(IV) Somatotropin Plus Thyrotropin Group (STH + TTH) — 26 animals

6 52 Cross section area of tissue components

The results obtained on planimetric study with the animals sacrificed 14 days after the operation have been presented in Table 1 The ultimately sought values could be recorded for both extremities in part of the material only and it was not considered appropriate to make a distinction between the results relating to the Achilles tendon of the left foot and of the right foot. Instead all results have been treated as a compound series

The results reveal that the smallest cross section area of the adhesions that developed around the tendon occurred in the somatotropin group, with the C and TTH groups next The area was largest in the group of animals under combined somatotropin and thyrotropin medication,

Although both extremities could not be included in the study in the case of all animals owing to the above mentioned causes the entire usable material was evaluated without exercising any selection The series are therefore comparatively extensive which is advantageous in the interest of reliable results

6.42 Cross section area of tissue components

The results obtained on planimetric study with the animals sacrificed five days after the operation can be found in Table 1 and are also shown by the graphs in Fig 28 separately for each of the four above mentioned groups The numerical values refer to the weights of the paper cut outs in mg (cf p 59) which are mutually comparable

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Statistical analysis by Student s *t* test, applied to the different groups in all possible combinations of two revealed *statistically highly significant differences between all groups except between the C and TTH groups*

The observation can thus be made that combined somatotropin and thyrotropin medication produced substantially superior adhesions as regards their cross section area No conclusive difference is seen between the control and thyrotropin groups but both are distinctly inferior to the STH + TTH group In the somatotropin group the adhesion cross section was smallest of all and it was clearly less than in any other group

6 5 Planimetric studies after 14 days

6 51 Experimental groups

The planimetric studies on specimens derived from rats sacrificed 14 days after the operation cover a material of altogether 105 rats The operative treatment medication and methods of investigation have been described in the foregoing (pp 27 30) The same material with some further animals added is also concerned in the subsequently reported tissue analysis studies (cf p 63) The results to be stated below therefore lend themselves to comparisons with the histological findings (p 76)

which differs essentially from the other groups According to Student s *t* test there is a *statistically highly significant difference between the STH + TTH group and each of the other groups* Between the C STH and TTH groups in their different combinations by two, at the most statistically almost significant differences can be noted

6 6 Comparison of results after 5 and 14 days

Comparison of the values recorded at 5 and 14 days after the operation reveals that a distinct regression in cross section area of the granulation tissue around the tendon takes place in the intervening period in all groups The mean cross section area was thus reduced by slightly more than 20 % in the C and STH + TTH groups but only by almost 9 % in the STH group Fig 28 furnishes a concise idea of the essential findings

The values found for the cross section area at 5 and at 14 days respectively display a *statistically significant difference in all but the STH group,* in which no significant difference was established (Table 1)

6 7 Statistical distribution of the cross section area

The logarithms of the individual cross section areas were plotted on a probability chart (i e their cumulative frequency graph was drawn) for each of the eight subgroups (5 and 14 days respectively and groups C STH TTH and STH + TTH) (Fig 29) The plots fall on straight lines with satisfactory accuracy indicating that the distribution is close to normal It is also seen that the straight lines have largely the same slope which is equivalent to nearly identical variances (quotient of S D and mean value cf Table 1) The intersection of the straight lines with the 50 % horizontal corresponds to the (geometric) mean in each subgroup, and these too agree fairly closely with the arithmetic means in Table 1

6 8 Comments

The planimetric study of the granulation tissue formed around the tendon after traumatization was undertaken in order to obtain additional data supplementing the information furnished by the tension tests The ideal would have been to achieve one to-one correspondence between cross section area and ultimate strength However since the specimens

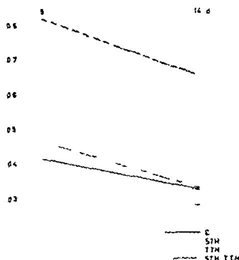


Fig 28 Comparison of adhesion cross sections The cross section area was largest in the STH + TTH group and smallest in the STH group The latter group also displayed the smallest reduction in cross section area from 5 to 14 days

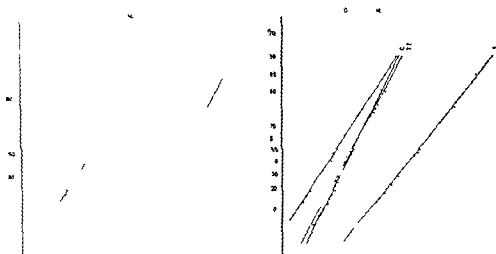


Fig 29 Individual values (logarithmic) of adhesion cross section area in the different groups after 5 and 14 days plotted as cumulative frequency curves on a probability chart The plots are fairly well consistent with straight lines indicating distributions close to normal and mutually closely parallel implying equal variances (S D /Mean) in the different test series

7 HISTOLOGICAL STUDIES

Histoquantitative methods One of the earliest procedures of quantitative tissue analysis was the counting of blood cells This implies a count of the number of cells in a compartment of given height per unit area In the preceding chapter a planimetric method has been described in which the area under investigation is divided into a number of squares by means of a superimposed screen When this net of the screen has one hundred squares the per cent composition of various tissues is easily determinable In the science of quantitative histology, this procedure is known as *area sampling* It has the drawback of being slow and cumbersome if a histologically complex tissue is concerned Granulation tissue with its numerous different components is such a tissue

Another method known as *point sampling* (CHALKLEY 1943) also makes use of a similar screen but the percentages of the different tissues are determined by the number of line intersections at which each of them is encountered If the procedure is repeated after an arbitrary shift of the screen a combination of the area and point sampling methods is obtained All these methods have been described in detail in ERANKO s (1955) text book

The relative distribution of areas can also be determined altogether without determining actual surface areas The principle according to which this can be done has long been used e g in the science of forest mensuration (ILVESSALO 1921) and in geology and the procedure is known as line surveying When the total area under examination is known the absolute quantity of each kind of tissue can be calculated from the relative figures

This *line sampling* method was applied and developed in quantitative histology by UOTILA (1940) and by UOTILA and KANNAS (1952) According to their procedure, a histological preparation is evaluated by drawing a straight line across the slide and determining in given relative units the aggregate lengths of intersects of this line running across each type of tissue

The line sampling method is excellently suited for determination of the proportions in which different cell groups occur in glandular tissues and

6 9 Synopsis of the planimetric studies

1 In the test series *after 5 days* the following observations we
The cross section of the granulation tissue was smallest in the somatotro and larger in the control, thyrotropin and somatotropin plus thyrotropin gro order All differences between groups were statistically highly significa between the control and thyrotropin groups

2 In the test series *after 14 days* the following observations wer
The cross section of the granulation tissue was again smallest in the som group which was followed by the control, thyrotropin and somatotropin plus th groups in this order Statistically highly significant differences were only es between the somatotropin plus thyrotropin group, in which the cross section was and all other groups

3 During the period *between 5 and 14 days a reduction in cross section are granulation tissue occurred in all groups The decrease was minimal in the somat group and did not amount to a statistically significant change*

it has been applied in histoquantitative studies on the thyroid gland by TALA (1952) and of the prostate by v HELLENS (1955) The repair of experimental fractures has been studied with its aid by KOSKINEN (1959 1965), and the behaviour of granulation tissue in particular was thus studied by SAIKKU (1956)

A convenient modification of the line sampling method involves the use of an *integrating eyepiece micrometer* (Fig 30) The measurements are then performed in the focal plane of the eyepiece lens by which a number of secondary sources of error will be eliminated The integrating eye piece manufactured by the LEITZ company has several micrometer drums any one of which can be used to shift the crosshair so that the transects of each kind seen along the sampling line can be accumulated individually to give immediate aggregate readings The integrating eye piece constitutes an excellent aid in microscopic anatomical quantitative studies

7 1 Experimental animals and groups

While in the studies on tensile strength the preparations were destroyed by rupture in the test the specimens used in the planimetric studies were usable for histological tissue analysis as well Furthermore the latter does not necessitate completely intact cross cuts and consequently also such specimens could be evaluated which had to be discarded in the planimetric studies because they were partially broken As a result the material concerned here is somewhat larger in extent than that of the planimetric series but individual comparison of both kinds of results specimen by specimen remains possible The total number of operated animals was 271 and in most instances both hind legs could be examined

The same subdivision into experimental groups was applied as in the other studies, namely

(I) Control Group (C) — 81 animals
(II) Somatotropin Group (STH) — 64 animals
(III) Thyrotropin Group (TTH) — 63 animals,
(IV) Somatotropin Plus Thyrotropin Group (STH + TTH) — 63 animals

The animals in each group received injections as described on p 30 One set of subgroups was sacrificed after five days and another after 14 days

for each group and subjected to the same operation Subsequent scrutiny showed that there are no noteworthy differences between the different control series It was therefore considered justified to lump the different partial series of each kind together in view of more convenient handling of the data

Combined in this manner, the experimental animals constitute the following groups

(I) Control Group (C) — 41 animals,
(II) Somatotropin Group (STH) — 34 animals,
(III) Thyrotropin Group (TTH) — 33 animals,
(IV) Somatotropin Plus Thyrotropin Group (STH + TTH) — 33 animals

7 32 Distribution of tissue components

Fibrocytes No closer distinction is made in this study between the different types of connective tissue cells This was not possible at the microscopic magnification employed in this work Endeavours were merely made to distinguish normal cells from inflammation cells

The results of the tissue analysis stating the amounts of fibrocyte tissue are seen in Fig 31 The table in this figure reveals that connective tissue cells occur in greatest abundance in the thyrotropin and somatotropin plus thyrotropin groups, while they are less numerous in the somatotropin and control groups The percentages show a *statistically significant difference of the TTH group from the STH + TTH group and a highly significant difference from the other two groups A highly significant difference still exists between the STH + TTH and C groups*

The observation can thus be made that in the specimens taken after five days fibrocytes occur in greater abundance in the hormone treatment group in which thyrotropin was administered

Ground substance The staining method employed in this work caused the ground substance to become blue or blue green It was the predominant tissue component in the preparations in all but the somatotropin group Some error in determination of the ground substance may be introduced by the fact that some of the fibrocytes lost their nucleus at sectioning and their cytoplasm was then difficult to distinguish from the ground substance

Fig 32 and its table show the results obtained in determination of the relative ground substance quantity at five days The quantity of ground

substance was highest in the somatotropin plus thyrotropin group and least in the somatotropin group Its relative quantity *in the STH + TTH group was higher than in the C and STH groups at a statistically highly significant level and significantly higher than in the TTH group while the C group showed ground substance more than in the STH group at a highly significant level*

Collagen The relative quantity of red staining collagen, too was determined with the aid of the integrating eyepiece micrometer (cf p 75) Scrutiny of the preparations revealed that the collagen was not completely evenly distributed all over the section in the specimens from animals sacrificed after five days It appears that the formation of collagen fibres started at certain centres of crystallization Such centres are the spots where collagen existed even before such as the tendon and the larger blood vessels Thus the first collagen fibres arrange themselves tangentially to the cross section of the tendon For this reason the tissue analysis measurements were made along a line progressing radially outward from the surface of the tendon

The results referring to the relative collagen quantity can be seen in Fig 33 and its table It can be seen from the table that collagen occurred at relatively highest quantity in the somatotropin group the control group ranging next Less collagen was seen in the granulation tissue in the thyrotropin group and least of all was recorded in the adhesions in the somatotropin plus thyrotropin group All values are clearly apart and it was found that *statistically highly significant differences exist between any two groups* The observation is thus made that hormone administration exerts a distinct effect on the formation of collagen in granulation tissue

Capillaries In the figures reflecting the amount of new blood vessels in the granulation tissue the areas covered by endothelial tissue and the lumen were included If there were leukocytes within the lumen they were not taken into account separately In the choice of the sampling line such points were avoided where for instance the large blood vessels of the mesotenon would have been traversed

The relative contribution of new blood vessels to the analyzed tissue in the different groups can be seen from Fig 34 The table in this figure reveals that the relative quantities of capillary space found in the different groups are not essentially different This implies that the administration of hormones did not substantially affect the relative quantity of blood vessels formed in the granulation tissue

for each group and subjected to the same operation Subsequent scrutiny showed that there are no noteworthy differences between the different control series It was therefore considered justified to lump the different partial series of each kind together in view of more convenient handling of the data

Combined in this manner the experimental animals constitute the following groups

(I) Control Group (C) — 41 animals,
(II) Somatotropin Group (STH) — 34 animals
(III) Thyrotropin Group (TTH) — 33 animals
(IV) Somatotropin Plus Thyrotropin Group (STH + TTH) — 33 animals

7 32 Distribution of tissue components

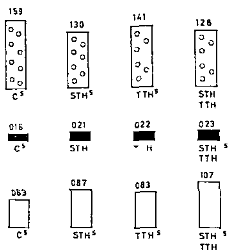
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The results of the tissue analysis stating the amounts of fibrocyte tissue are seen in Fig 31 The table in this figure reveals that connective tissue cells occur in greatest abundance in the thyrotropin and somatotropin plus thyrotropin groups while they are less numerous in the somatotropin and control groups The percentages show a *statistically significant difference of the TTH group from the STH + TTH group and a highly significant difference from the other two groups A highly significant difference still exists between the STH + TTH and C groups*

The observation can thus be made that in the specimens taken after five days fibrocytes occur in greater abundance in the hormone treatment group in which thyrotropin was administered

Ground substance The staining method employed in this work caused the ground substance to become blue or blue green It was the predominant tissue component in the preparations in all but the somatotropin group Some error in determination of the ground substance may be introduced by the fact that some of the fibrocytes lost their nucleus at sectioning and their cytoplasm was then difficult to distinguish from the ground substance.

Fig 32 and its table show the results obtained in determination of the relative ground substance quantity at five days The quantity of ground



5 days	Group C	STH	TTH	STH +TTH
Capillaries	159	130	141	128
Leukocytes	16	21	22	23
Empty space	63	87	83	107

No statistically significant differences between groups

Fig 34 Relative amounts (top to bottom) of capillaries leukocytes and empty space in the adhesions after five days No statistically significant differences (Inscribed values as in Fig 31)

Leukocytes The inflammation cells in the preparations are distinguish able by their smaller size and their fragmented nucleus As a rule they were rather scanty only a few cells per transect Leukocytes seen in the lumen of traversed blood vessels were not taken into account In the majority of the preparations the number of leukocytes was less than 4 % In some specimens this figure was considerably exceeded which were accordingly considered to be inflamed and were discarded The last mentioned preparations also contained separate leukocyte accumulations in which bacteria could be observed In many of these cases the epithelium at the site of the wound had failed to close and it was encrusted with bacteria present in great number

The results can be seen in Fig 34 The values found for the relative quantity of leukocytes are not essentially different This implies that the administration of hormones did not substantially influence the number of leukocytes in the granulation tissue investigated

Empty space The sections contained some areas from which the stainable matter had been washed off in preparation It seems obvious that this has been interstitial matter seeing that cracks which occur now and then as artefacts are readily recognizable

The occurence of empty spaces in the different groups is seen from Fig 34 Empty spaces were seen to occur in somewhat greater abundance in the somatotropin plus thyrotropin group than in any other but the differences are not very notable

7.4 Tissue analysis after 14 days

7.41 *Experimental groups*

The material used in quantitative tissue analysis comprises altogether 130 animals sacrificed 14 days after the operation. It turned out to be a difficult task to prepare good cuts of the hard tendon tissue and microscopic preparations were not obtained from all animals.

By combining the subgroups of animals with different operating dates the following groups were obtained:

(I) Control Group (C) — 40 animals
(II) Somatotropin Group (STH) — 30 animals
(III) Thyrotropin Group (TTH) — 30 animals
(IV) Somatotropin Plus Thyrotropin Group (STH + TTH) — 30 animals

7.42 *Distribution of tissue components*

Fibrocytes. In the specimens taken at 14 days the fibrocytes are squeezed flat between the collagen fibres. Since the fibres have no consistent orientation, the tissue analysis takes part of the fibrocytes into account in their longitudinal extension.

The results can be seen in Fig. 35 and its table. The relative quantity of fibrocytes in the specimens taken at 14 days was found to be closely the same in all groups and there are no statistically significant differences.

Ground substance. Less ground substance occurred in the specimens taken at 14 days than in those from animals sacrificed five days after the operation. Between the strongly red stained collagen fibres and close to them the ground substance occasionally assumed a brownish tinge, which may be merely due to reflection, seeing that elsewhere the ground substance was stained blue in normal manner.

The results can be seen in Fig. 36 and its table. At 14 days, as at five days, the relative quantity of ground substance was still highest in the somatotropin plus thyrotropin group and lowest in the somatotropin group. However, the differences have become considerably less and their statistical significance is lower in level than at five days. The quantity of ground substance is *greater at a statistically highly significant level in the STH + TTH and TTH groups than in the STH group. That in the STH +*

TTH group still exceeds significantly the quantity in the C and TTH groups, and the quantity in the C group is significantly higher than in the STH group

Collagen In the specimens taken at 14 days collagen was the predominant tissue component in all experimental groups extending as a uniform network all over the preparation. As in the case of the animals sacrificed at five days the quantitative determinations were made along a line radial to the tendon cross section. This renders the observations relating to five and to 14 days mutually comparable.

The occurrence of collagen 14 days after the operation can be seen from Fig 37 and its table At 14 days too the highest relative collagen quantity was seen in the somatotropin group The differences between the other groups are small There is no longer any statistically significant difference between the TTH and C groups *The STH group still displays a statistically significant difference from the C group and highly significant differences from the other treatment groups*

Capillaries In determining the quantity of new blood vessels the endothelial cell tissue was also included in addition to the lumen In all other respects too the same principles were followed as in the analyses relating to five days of hormonal treatment

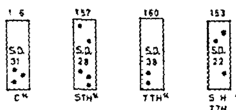
The results are shown in Fig 38 It can be seen that the relative abundance of capillaries was not greatly different in the different groups It is concluded that the administration of hormones did not essentially affect the formation of new blood vessels

Leukocytes The number of leukocytes at 14 days was reduced in every group from that recorded at five days In most of the preparations no leukocytes at all were seen

The relative quantity of leukocytes which was very small in all groups is seen from Fig 38 No great differences can be noted between the different groups

Empty space Between the collagen fibres there occur areas from which all ground substance has been washed away The area within the lumen of blood vessels was not included in the empty spaces

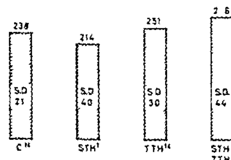
The relative quantities of empty space are shown by Fig 38 Unstained, empty spaces occurred in equal relative quantity in the different groups It can be concluded that the hormone administration had no effect on the relative amount of matter washed off



Group	Mean	S D	Var	Difference compared to C	STH	TTH
C	156	31	0 20			
STH	157	28	0 18			
TTH	160	38	0 24			
STH +TTH	153	22	0 14			

*** Statistically highly significant
* Statistically significant
* Statistically almost significant

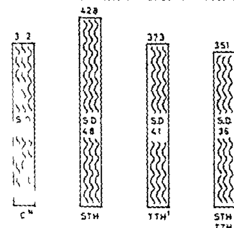
Fig 35 Relative quantities of fibrocytes in the adhesions after 14 days There are no longer any statistically significant differences (Mean values on top and inscribed S D values Thousandths of mean transect length likewise in the table)



Group	Mean	S D	Var	Difference compared to C	STH	TTH
C	238	21	0 09			
STH	214	40	0 19	**		
TTH	251	30	0 12		***	
STH +TTH	276	44	0 16	**	***	**

*** Statistically highly significant
** Statistically significant
* Statistically almost significant

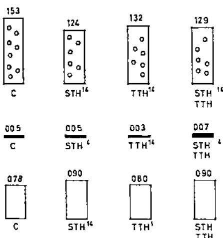
Fig 36 Relative quantities of ground substance in the adhesions after 14 days The amount is still highest in the STH + TTH group at a statistically significant level but the differences are about to become equalized (Inscribed values as in Fig 35)



Group	Mean	S D	Var	Difference compared to C	STH	TTH
C	372	27	0 07			
STH	428	48	0 11	**		
TTH	373	41	0 11		***	
STH +TTH	351	36	0 10	***	* *	**

* * Statistically highly significant
** Statistically significant
* Statistically almost significant

Fig 37 Relative quantities of collagen in the adhesions after 14 days The amount is still greatest at a statistically significant level in the STH group but the differences are about to become equalized (Inscribed values as in Fig 35)



14 days	Group C	STH	TTH	STH +TTH
Capillaries	153	124	132	129
Leukocytes	5	5	3	7
Empty space	78	90	80	90

No statistically significant differences between groups

Fig 38 Relative amounts (top to bottom) of capillaries leukocytes and empty space in the adhesions after 14 days equal in the different groups (Inscribed values as in Fig 35)

7 5 Comparison of results after 5 and 14 days

Comparison of the tissue analysis results reported in the foregoing reveals that remarkable changes have taken place in all hormone treatment groups during the period from five to 14 days in the per cent distribution reflecting the structure of the granulation tissue The changes noted with regard to the most essential tissue components namely fibrocytes ground substance and collagen are illustrated by Table 2

It is seen that the relative collagen quantity increased in all groups but decidedly most strongly in the STH + TTH group while the increase was least in the STH group The amount of fibrocytes is seen to have gone down the effect may be partially due to flattening of the cells The ground substance decreased consistently in all groups its change too was strongest in the STH + TTH and least in the STH group

The diagram in Fig 39 gives a clear idea of the changes established by the tissue analysis measurements The smallest changes are seen to have occurred in the STH group Moreover the distributions tend to become largely equal by the end of the 14-day period It is conceivable that virtually the same per cent composition of the granulation tissue might have been obtained in all groups if the experiment had been continued.

In Plate I (between pp 88 and 89) colour reproductions of micrographs representing the different groups after five and 14 days are presented They show the circumstances stated above as they are revealed to the examiner

7 6 Comments

In most studies concerning granulation tissue such tissue is observed to contain an ample number of leukocytes and giant cells, which confuse the microscopic picture The profuse occurrence of such cells is a sign of inflammation and foreign body irritation, which has sometimes been used to provoke formation of granulation tissue (SELYE 1953, STEBBINS and STOERK 1955, SAIKKU 1956, VILJANTO and KULONEN 1962) However, the difficultly controllable inflammation process often causes great disturbance of the repair (DUPONT 1959) thus impeding the study of the effects exerted by extraneous factors, such as hormones In the present work formation of granulation tissue around the tendon was achieved without these annoying factors The advantage of this is that no marked secondary inflammation phenomenon can obscure such hormonal effects as there may be

It is evident already from clinical experience in itself that the granulation tissue becomes resistant against infection, i e against bacterial enzymes and toxins at a certain stage. Likewise its response to hormones obviously soon decreases as the tissue ages (WHIPPLE 1940) According to the first law governing the general mechanism of action of hormones, hormones affect the intensity and rate of the granulation process (WILLIAMS 1955)

Table 2 Changes in relative quantity of fibrocytes ground substance and collagen from 5 to 14 days

Group	Fibrocytes			Ground substance			Collagen		
	5 days	14 days	Change per cent	5 days	14 days	Change per cent	5 days	14 days	Change per cent
C	162	156	− 0 6	365	238	− 12 7***	235	372	+ 13 5***
STH	170	157	− 1.3	258	214	− 4 4 **	336	428	+ 9 2**
TTH	233	160	− 7.3**	340				373	+ 19 1**
STH + TTH	193	153	− 4 0**	461					+ 35 1**

= Statistically highly sig

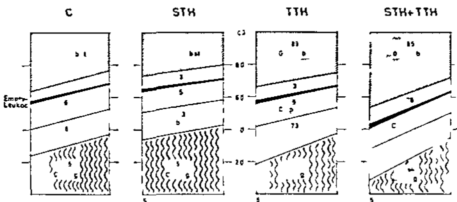


Fig 39 Graphical presentation of the changes the relative amounts of different tissue components have undergone with progressing maturation of the granulation tissue The most powerful change has occurred in the STH + TTH group — The slope of the graphs reflecting the change is consistent with the corresponding tension test results cf particularly Fig 21

When the process is completed hormones have no longer any influence on it

In the tissue analytic studies that were carried out the differences between the hormonal treatment groups could be seen to have levelled out in the test series at fourteen days, which is consistent with the foregoing The relative composition of the tissue in the different hormonal treatment groups then begins to resemble that of the controls Of course, the regeneration taking place continuously in the organism is also subject to hormonal effect This is thought to account for the fact that in various endocrinopathies despite the presence of a distinct clinical picture no pathological findings can be elicited on histological examination of the connective tissue. A stupendous disturbance is clearly needed for such manifestation to occur

In the series of specimens taken at five days the relatively greatest amount of collagen was found in the STH group Correspondingly the quantity of ground substance was lowest in the same group The action of somatotropin to cause increased formation of collagen has also been noted by Scow (1951) and Banfield (1958) The increased proliferation of fibroblasts reported by Taubenhaus and Amromin (1950) was not observed on the other hand The increased collagen quantity observed here corroborates the opinion presented by Silberberg et. al (1964) that somatotropin accelerates the development of the collagen fibres The appearance

7.6 Comments

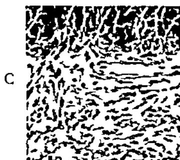
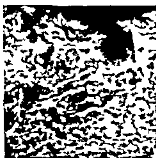
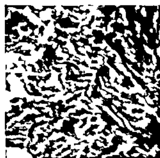
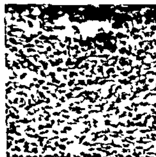
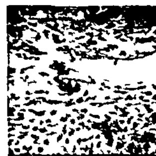
In most studies concerning granulation tissue such tissue is observed to contain an ample number of leukocytes and giant cells which confuse the microscopic picture. The profuse occurrence of such cells is a sign of inflammation and foreign body irritation which has sometimes been used to provoke formation of granulation tissue (Selye 1953, Stebbins and Stoerk 1955, Saikku 1956, Viljanto and Kulonen 1962). However the difficultly controllable inflammation process often causes great disturbance of the repair (Dupont 1959) thus impeding the study of the *effects exerted by extraneous factors, such as hormones. In the present* work formation of granulation tissue around the tendon was achieved without these annoying factors. The advantage of this is that no marked secondary inflammation phenomenon can obscure such hormonal effects as there may be.

It is evident already from clinical experience in itself that the granulation tissue becomes resistant against infection, i.e., against bacterial enzymes and toxins at a certain stage. Likewise, its response to hormones obviously soon decreases as the tissue ages (Whipple 1940). According to the first law governing the general mechanism of action of hormones, hormones affect the intensity and rate of the granulation process (Williams 1955).

Table 2. Changes in relative quantity of fibrocytes, ground substance and collagen from 5 to 14 days

Group	Fibrocytes			Ground substance			Collagen		
	5 days	14 days	Change per cent	5 days	14 days	Change per cent	5 days	14 days	Change per cent
C	162	156	−0.6	365	238	−12.7***	235	372	+13.5**
STH	170	157	−1.3	258	214	−4.4***	336	428	+9.2**
TTH	233	160	−7.3**	340	251	−8.9***	182	373	+19.1*
STH + TTH	193	153	−4.0**	461	276	−18.5***	87	351	+35.1**

*** = Statistically highly significant, ** = significant, * = almost significant difference

	5 days	14 days	
C			C
STH			STH
TTH			TTH
STH + TTH			STH + TTH

of collagen in the wound is a sign of maturation of the granulation tissue (JACKSON 1958) In his histoquantitative studies SAKKU (1956) observed that somatotropin caused maturation of granulation tissue. In the present work the structure of the tissue displayed the least change in the period from five to 14 days just in the STH group which speaks in favour of early maturation in these instances

The inference can thus be drawn that somatotropin promotes the maturation of the granulation tissue and the collagen formation In other words *somatotropin accelerates and stimulates the second, or collagen, phase in the formation of granulation tissue*

The action of thyrotropin is to increase the fibrocyte and mucopoly saccharide quantity and to reduce that of collagen In the thyrotropin group the greatest number of fibrocytes was found in the series referring to five days with statistically highly significant differences in comparison to the C and STH groups In the literature, thyrotropin is stated to stimulate the mucopolysaccharide formation of connective tissue (ASBOE HANSEN 1959) Increased amount of connective tissue cells could also be observed by WEGELIUS and JOKINEN (1962) GYLLING (1964) achieved with thyrotropin an increase in the relative ground substance quantity This circum stance becomes visible in the 14-day series where the relative ground substance quantity is clearly greater in the TTH than in the STH group with a statistically highly significant difference However the conclusion is not thought to be appropriate that these agents would be antagonistic to each other It appears likely that *thyrotropin stimulates the first, or productive phase of the formation of granulation tissue*

Since it was reasoned that thyrotropin stimulates the productive and somatotropin the collagen phase in the formation of granulation tissue, the result of their simultaneous administration should be a great amount of granulation tissue It is seen from the preceding and following chapter that this is indeed true

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PLATE I (opposite)

Colour reproductions of micrographs from details adjacent to the tendon surface in the preparations (magnification ×400) The tendon lies at the top of the micrographs — When stained by Pentachrome II collagen acquires an intense red colour and ground substance appears blue

After five days red collagen is already seen in ample amount in the somatotropin group The group with synergistic action of somatotropin and thyrotropin still displays very little collagen at this stage while the quantity of blue ground substance is high

After 14 days a high quantity of collagen is seen in all preparations indicating maturation of the granulation tissue

7 7 Synopsis of the histological studies

1 In the test series after 5 days the following observations were made

a) *Fibrocytes occurred in relatively greatest amount in the thyrotropin group, with statistically highly significant or significant differences from all other experimental groups The quantity of fibrocytes in the somatotropin plus thyrotropin group was greater than in the control group at a statistically significant level*

b) *Ground substance occurred most in the somatotropin plus thyrotropin group and it gradually decreased in amount in the control, thyrotropin and somatotropin groups The quantity noted in the group with combined treatment differed from those in the control and somatotropin groups at a statistically highly significant level and from that in the thyrotropin group at a significant level In the somatotropin group it was highly significantly less than in the controls*

c) *The relative quantity of collagen was highest in the somatotropin group which was followed by the control, thyrotropin and somatotropin plus thyrotropin groups, in this order All groups displayed statistically highly significant differences from each other*

d) The administration of hormones had no noteworthy effect on the quantities of capillaries leukocytes and empty spaces

2 In the test series after 14 days the following observations were made

a) *In the relative amount of fibrocytes no statistically significant differences between the hormonal treatment groups could be noted nor between them and the controls*

b) *The occurence of ground substance was still highest in the somatotropin plus thyrotropin group, followed by the thyrotropin, control and somatotropin groups, but the differences between groups had largely levelled out The control group still differed at a statistically significant level from the combined hormonal treatment and somatotropin groups*

c) *The relative quantity of collagen was again highest in the somatotropin group, with statistically significant differences from the controls and other groups The differences between the other groups had become equalized*

d) No effect of hormonal medication on the relative quantities of capillaries leukocytes and empty space was noted

3 Comparison of the results obtained in the test series after 5 days and after 14 days revealed that *the relative quantity of collagen had increased in all groups, most of all in the somatotropin plus thyrotropin group and least in the somatotropin group The relative amount of fibrocytes decreased during the period in question in all groups, most markedly in the thyrotropin group The ground substance quantity showed a similar decrease, which was strongest in the group with combined treatment and least in the somatotropin group*

8 COLLATION OF FINDINGS

8.1 Comparison of the results obtained in tension tests, planimetric studies and histoquantitative studies

The results yielded by the different methods of investigation can be approximately related with each other on the basis of Hooke's law, which is expressed by the formula

$$F = E \cdot A \cdot \frac{\lambda}{l}$$

The formula states that the force F producing a given elongation λ is proportional to this elongation and to the cross section area A of the specimen and inversely proportional to the specimen's length l. The coefficient of proportionality E (the modulus of elasticity) is a constant dependent on the structure of the material and it is higher accordingly as the substance is more compact and firm. The strength of granulation tissue, again, depends on its relative collagen quantity (WHIPPLE 1940).

The relationships of elongation and force in the test series carried out after 5 and 14 days may be mutually compared by examining the forces consistent with a given elongation. The correspondence can only be approximate because the departure from linearity caused by the intermediate yielding was disregarded. It is also to be noted that, owing to destruction of the specimens in the tension tests, the planimetric data have been derived from a different set of specimens. In all groups the cross section area of the adhesions could be seen to diminish from 5 to 14 days, most of all in the STH + TTH group.

In the control group (C) the force consistent with a given elongation (λ = 50 units = 8.33 mm) was the same in the tests after 5 days and after 14 days. Since the cross section area had decreased, an increase in the relative amount of collagen must have taken place in ... enr, ... or the resistance against deformation (the produc ... wou ... g down. This was indeed corroborated by the ... ysi

In the STH group the force for one and the same elongation diminished slightly during the period from 5 to 14 days This indicates that there has been a reduction of the *EA* product which means that the relative quantity of the collagen did not increase very much. It is seen that according to the tissue analysis the percentage of collagen increased least of all in this particular group

In the TTH group a distinct increase of the force from 5 to 14 days was noted Since here too, the cross section area was reduced the relative collagen quantity must necessarily have increased quite considerably This conforms to the finding on tissue analysis that the collagen percentage was doubled in this group

The tensile strength in the STH + TTH group was lowest among all values at 5 days but it increased to be the highest value at 14 days This unexpected change took place in conjunction with a decrease in cross section area of the adhesions exceeding those in all other groups These facts indicate a powerful increase of the collagen percentage. In fact the tissue analysis showed that the relative amount of collagen has increased by a factor of 4 in this group

The observation can thus be made that the results obtained by the different methods employed in this work are mutually well consistent in each individual point.

8 2 Elastic properties and composition of the granulation tissue

On the theory that the structure of a tissue in the first place its content of given components together with the cross section area determines its elastic constants according to some simple relationship an attempt has been made to relate the apparent modulus of elasticity of the adhesion tissue to the relative collagen content and absolute cross section area in the different groups considered in this study If such a relationship holds true with sufficient accuracy one of the three quantities can be determined by calculation if the other two are known

The formula involved is that representing Hooke s law which we may write

$$E = \frac{F \quad l}{A \quad l}$$

Table 3 Forces consistent with a given elongation (l = 50 units crorresponding to 8.33 mm elongation) in the different test series derived from the graphs in Fig 23 (p 52) for comparison of the results

Group	Relative units		Absolute g	
	5 days	14 days	5 days	14 days
C	165	165	1270	1270
STH	200	190	1540	1463
TTH	150	180	1155	1386
STH + TTH	125	220	962	1694

If the values in Table 3 previously derived from the graphs constructed on the basis of the mean relationship between the tensile force F and the elongation λ (cf p 52) are substituted, we find the figures stated in the tabulation below It should be noted that these values of E are not consistent with any physical dimension in common use

Group		E	Relative collagen quantity
C	5 days	239	0 235
STH	5 days	392	0 336
TTH	5 days	192	0 182
STH + TTH	5 days	89	0 087
C	14 days	306	0 372
STH	14 days	413	0 428
TTH	14 days	333	0 373
STH + TTH	14 days	202	0 351

Despite some deviations *the two sets of values are obviously consistent in expected manner* However, in view of the approximate character of all values involved in this consideration it is not thought to be appropriate

to carry it to the otherwise logical conclusion of presenting positive formulae by which e g the strength properties of tissue could be calculated from measurements performed on its histological preparation or the cross section area of the granulations from the strength and the tissue analysis data

8.3 Absolute quantity of the tissue components

Since identical subjects were concerned in the planimetric studies and in the tissue analysis reported in the foregoing, these data can be considered in combination for each individual preparation and not merely on the mean value level

When the per cent contribution of each tissue component to the entire cross section and the cross section area are known, the absolute area covered by each component can be calculated This has been done for each individual preparation with respect to three tissue components which were considered most important to be studied in this manner, namely fibrocytes ground substance and collagen The means of the results from this computation with their standard deviations and variances have been presented in Tables 4—6 and in Fig 40

Table 4 Comparison of the absolute fibrocyte quantities in the granulation tissue revealing statistically highly significant changes under the effect of hormones

	Var	S D	Mean	Group		STH ↓	TTH ↓	STH +TTH ↓ Difference compared to					
5 days	0.31	19	68	C	* *	*		***	C	50	16	0.32	14 days
	0 42	22	52	STH	**	*	*	***	STH	42	14	0.33	
	0.52	58	111	TTH	**	*	*	***	TTH	53	18	0 34	
	0.28	44	1ɔ6	STH +TTH		***	***	*	STH +TTH	95	45	0 47	
	Difference compared to				↑ C	↑ STH	↑ TTH		Group	Mean	S D	Var	

Squares on diagonal between both halves of the table Difference 5 days – 14 days

Unit mg of paper cut-out weight

** Statistically highly significant
** Statistically significant
* Statistically almost significant

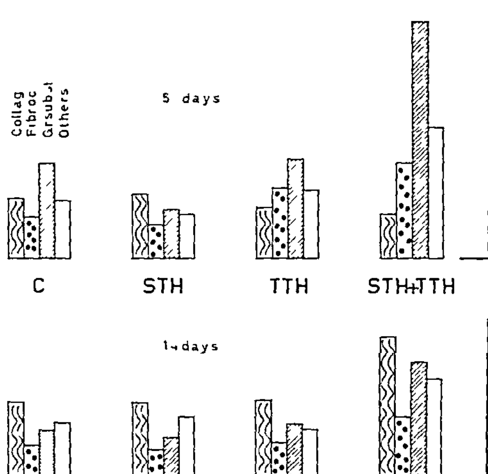


Fig 40 Comparison of the absolute quantities of different tissue components in the granulation tissue after 5 and 14 days

Statistical analysis of the results stated in the tables reveals highly significant differences between the values relating to five days and 14 days in all but the STH group and with respect to all tissue components considered here In the STH group only an almost significant difference between five and 14 days is seen in all three quantities This constitutes further proof in support of the action of somatotropin causing rapid maturation of the granulation tissue, as does also the small amount of cells and ground substance encountered in the preparations of the STH group The collagen quantity is high on the other hand, which implies that *somatotropin obviously promoted the process of the collagen phase*

Table 5 Comparison of the absolute ground substance quantities in the granulation tissue Statistically highly significant changes are observed [1])

	Var	S D	Mean	Group		STH ↓	TTH ↓	STH +TTH ↓ Difference compared to					
5 days	0 26	40	151	C	***	*		***	C	76	24	0.32	14 days
	0.35	27	77	STH	***	*	**	***	STH	62	28	0 45	
	0 34	54	158	TTH		***	***	**	TTH	83	28	0.34	
	0 25	95	377	STH +TTH	***	***	***	***	STH +TTH	184	18	0 42	
	Difference compared to				↑ C	↑ STH	↑ TTH		Group	Mean	S D	Var	

Squares on diagonal between both halves of the table Difference 5 days – 14 days

Unit mg of paper cut-out weight

*** Statistically highly significant
** Statistically significant
* Statistically almost significant

Table 6 Comparison of the absolute collagen quantities in the granulation tissue Statistically highly significant changes are ob erved [1])

	Var	S D	Mean	Group		STH ↓	TTH ↓	STH +TTH ↓ Difference compared to					
5 days	0 25	24	97	C	*			*	C	120	32	0.38	14 days
	0.33	31	101	STH		*		***	STH	117	36	0.31	
	0.25	20	83	TTH	**	**	***	**	TTH	121	30	0.25	
	0.34	24	71	STH +TTH	***	***	*	***	STH +TTH	223	65	0 29	
	Difference compared to				↑ C	↑ STH	↑ TTH		Group	Mean	S D	Var	

Squares on diagonal between both halves of the table Difference 5 days – 14 days

Unit mg of paper cut-out weight

** Statistically highly significant
** Statistically significant
* Statistically almost significant

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[1]) Closer study of the tables 4 – 6 opens many new interesting perspectives No comments are presented on such aspects since they go beyond the problems outlined for the present study

— Mature granulation tissue no longer increases in any noteworthy degree consistently, the change in cross section area from 5 to 14 days was least with somatotropin

— The collagen percentage was highest in both test series

— Immature ground substance occurred least in both series

— The composition of the mature granulation tissue underwent the least change between the times of 5 and 14 days

— The absolute quantity of collagen increased least of all during the period from 5 to 14 days

The present studies thus corroborate and complement the opinion presented before by Scow (1951) Spain and Molomut (1953), Saikku (1956) Banfield (1958) and Silberberg et al (1954), that somatotropin accelerates the collagen formation

Thyrotropin was found to stimulate the productive phase of connective tissue formation, accelerating the proliferation of fibrocytes and the formation of ground substance The following circumstances relating to this group in the tests after five days and after 14 days bear evidence of this

— The low ultimate tensile strength after five days indicates that the productive phase is still in progress and there has been little collagen formation

— Immaturity of the tissue at five days seems to be borne out by the powerful increase in ultimate tensile strength between 5 and 14 days

— A high value of the ultimate elongation was recorded in the five day series

— The adhesions were large in cross section area evidencing lively formation of connective tissue.

— The percentage of collagen was still low at five days

— The quantity of ground substance was high

— The highest number of cells at five days was recorded in this group

— Suggestive of immaturity of the tissue are the great changes it under went between 5 and 14 days

— The absolute number of cells was high

— The absolute quantity of ground substance too, was second highest among the different groups

It should be noted that the organism possesses an efficient regulating mechanism which counteracts the influence of thyrotropin (Brunish 1960)

The contention that thyrotropin promotes the production of connective tissue is also supported by IVERSEN and ASBOE HANSEN's (1952) and ASBOE HANSEN's (1959) observation of increase of the mucopolysaccharides. Another indication to this effect is the formation of exophthalmus (BOAS and SOFFER 1950, DOBYNS and STEELMAN 1953).

On simultaneous administration of *somatotropin and thyrotropin*, stimulation of the connective tissue production was observed at first and then of collagen formation. The following circumstances noted in the test series after five days and after 14 days for instance speak in favour of initially lively cell division and formation of ground substance.

— The tensile strength of the tissue was lowest of those recorded in the five day series.

— The change in tensile strength during the period between 5 and 14 days was greatest in this group.

— The yielding of the loose tissue had the highest value in the five day series.

— The ultimate elongation was largest among those referring to five days.

— Much granulation tissue was formed and the largest adhesion cross sections were recorded.

— The lowest collagen percentage at five days occurred in this group.

— The lowest absolute collagen quantity at five days occurred in this group.

— Cells were noted in ample number.

— The quantity of ground substance was highest in the five day as well as the 14-day series.

The following indications of subsequent invigoration of the collagen formation were obtained:

— Highest tensile strength in the 14-day series.

— Highest increase of tensile strength from 5 to 14 days.

— The yielding was no longer highest in the test after 14 days.

— The compacted tissue was not elongated most of all in the 14-day series either.

— The highest absolute collagen quantity in the 14-day series was recorded in the somatotropin plus thyrotropin group.

It is concluded that much granulation tissue has time to be formed and the strongest adhesions are produced after collagen has appeared in the

picture In connection with fractures of the long bones this phenomenon has caused massive, hypertrophic callus formation (KOSKINEN 1959)

One has to exercise certain caution in any attempt to apply the experimental results in actual clinical practice The fact has already been pointed out that the tendon consists of highly differentiated tissue which therefore has low regenerative ability As a matter of fact the repair of a tendon takes place from the periphery and indeed by means of the adhesion formation (WEHNER 1923, HUECK 1923 NÄRVI 1926 SKOOG *et al* 1954, ASHLEY et al 1960 POTENZA 1962) What has been said above is therefore also applicable in cases in which it is desired to restore the continuity of a tendon In actual truth the formation of adhesions is then desirable, because it alone is able to knit the severed ends together once more Any attempt at reconstruction of a severed tendon involving endeavours to *block* the formation of adhesions e g by means of interpositions (WECKESSER et al 1949, MCKEE 1945 STINCHFIELD 1950 LEVEEN 1949), is foredoomed to failure The real aim should be to *control* the formation of adhesions

In tendorrhaphy the desirable events are rapid consolidation, early collagen formation and a small scar In this light the use of somatotropin in connection with tendorrhaphies would seem to be indicated Cortisone *has been found to prevent the formation of adhesions, resulting in separation* of the tendon fragments (CARSTAM 1953) If the aim is to attach the tendon firmly to the bone or to perform tenodesis a strong massive scar is desirable Administration of somatotropin in combination with thyrotropin would then seem appropriate In tenolysis, again early formation of a scar is not wanted In such instances thyrotropin alone can be administered The writer s clinical experiences which are small in extent so far, are encouraging (Fig 42)

In general surgery, too e g in various hernias a massive and firm scar is desirable This is an instance in which combined hormonal treatment may be tried out The said hormones are also used in thorax surgery (UOTILA PERASALO and VAPAAVUORI 1955) and expressly in tuberculosis (CARSTENSEN PAULSEN and RUDBERG-ROOS 1954)

In *soft tissue surgery the administration of hormones* has the *advantage* that they need be given during a short period only This implies that immunity has not time to develop and no general effects can become established It should be stressed however, that atraumatic technique (BRUNELL 1921) and aseptics are absolutely primary in surgery on the limbs and cannot be replaced with any hormonal expedients

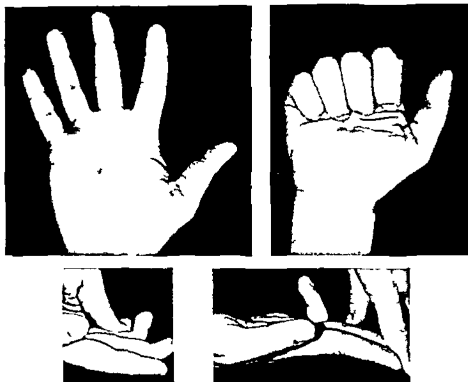


Fig 42 Patient B H 37 years male Both flexor tendons of the fourth digit were cut through in the distal part of the palm After primary tendorrhaphy the patient was given 20 U S P units somatotropin (Somacton Ferring Ab Malmo Sweden) every second day during two weeks Absolutely complete restoration of the function of both tendons was achieved

In various endocrinopathies such as acromegaly excessive growth and fibrosis are encountered as a consequence of overabundant secretion of the hormones in question The regeneration of connective tissue is stimulated and the skin is thick and high in collagen content (ASBOE-HANSEN 1954) The writer is somewhat inclined to consider also pathological states such as cheloid tendency and Dupuytren s contraction to be secondary manifestations of hormonal disturbance

For the behaviour of granulation tissue under the effect of hormones a certain numerical expression could be found in the studies reported here. Future work will no doubt show the extent in which it can be usefully employed in clinical research. In addition to surgical trauma also the effects of endocrinectomies adrenal hormones vitamins and other factors may be illuminated by the procedures applied in this work.

10 CONCLUSIONS

In the studies that have been carried out thyrotropin somatotropin and the combination of both were found to have a distinct effect on the adhesions formed around a traumatized tendon of the rat. The following can be stated in answer of the questions outlined earlier in this work

1 (a) The ultimate tensile strength at the end of the productive phase (after five days) was highest in the animals to whom somatotropin had been given followed in declining order by the control thyrotropin and somatotropin plus thyrotropin groups

(b) The ultimate tensile strength in the collagen phase (after 14 days) was highest in the combined somatotropin plus thyrotropin treatment group It was clearly less in the thyrotropin and control groups and least of all with the animals to whom somatotropin had been administered

(c) The increase in ultimate tensile strength during the period from 5 to 14 days was greatest in the group with combined somatotropin and thyrotropin treatment and least in the somatotropin group

(d) The hormonal treatments could not be observed to exert any statistically significant effect on the elongation

2 (a) The cross section area of the adhesions after five days was largest *in the somatotropin plus thyrotropin group*, followed in declining order by the thyrotropin, control and somatotropin groups

(b) The same order of the groups as above was noted in respect of cross section area of the adhesions after 14 days

(c) The cross section area of the adhesions decreased during the time from 5 to 14 days in all groups The change was least in magnitude with the animals under somatotropin treatment

3 (a) Histological examination after five days revealed the following facts

— The relative collagen quantity was highest in the somatotropin group followed by the control, thyrotropin and somatotropin plus thyrotropin groups

— Fibrocytes occurred in greatest abundance in the group of animals under thyrotropin treatment

— Ground substance was found in relatively highest quantity in the somatotropin plus thyrotropin group, this quantity decreased gradually according to the succession controls thyrotropin group somatotropin group

— No differences between groups were noted in respect of any other tissue components present in the adhesions

(b) Histological examination after 14 days revealed the following facts

— The relative collagen quantity was again highest in the somatotropin group but the differences between the other three groups had levelled out

— The greatest abundance of ground substance was noted in the group with combined somatotropin and thyrotropin treatment The differences between groups were becoming less also in respect of the relative ground substance quantity

— No differences between the different groups were observed in regard of any other tissue components including the relative fibrocyte quantity

(c) The following changes took place in the histological structure of the tissue during the period from 5 to 14 days

— The relative collagen quantity increased in all groups most of all in that with combined somatotropin and thyrotropin treatment and least of all in the group with exclusive somatotropin administration

— The number of fibrocytes decreased in all groups most strongly in the thyrotropin group

— The quantity of ground substance too decreased in all groups The change was again greatest in the group with combined treatment and least in the somatotropin group

4 The differences in tensile strength established between the different groups and the change of the tensile strength between 5 and 14 days were found to correlate with the changes in cross section area and structure of the tissue Owing to the relationship between the results

produced by the different methods, one of the three quantities could be mathematically determined when the values of the other two were known

5 The granulation coming into existence around an injured tendon is subject to the same laws as the healing of a wound in general Hormones were concluded to have the following influence on the formation of granulation tissue

(a) Thyrotropin stimulated the productive phase of granulation formation

(b) Somatotropin promoted the collagen formation and caused rapid maturation of the granulation tissue

(c) Simultaneous administration of thyrotropin and somatotropin at first accelerated the production of granulations, at a later time collagen was formed in profusion.

11 SUMMARY

The adhesions produced around a traumatized tendon and the effects exerted on them by the hypophyseal hormones somatotropin and thyrotropin have been studied in experiments on the rat s Achilles tendon Both hind legs of 355 experimental animals were subjected to operation involving trauma to the tendon One series of studies was made five days after the traumatizing operation and another after 14 days Both series include four groups, namely the control somatotropin thyrotropin and combined somatotropin plus thyrotropin groups

Three different methods of investigation were employed the results of which can be brought into mutual relationship thus enabling them to be checked to a certain extent

1 *Tension tests* The tensile force acting on the tendon and on its adhesions was recorded as a function of the elongation in a specially designed tension testing apparatus The tendon was invariably first detached from the bone a force four times as high was required to overcome the soft tissue adhesions This has been ascribed to the fact that the tendon adjoins on bone by a small part of its area only and to the small ultimate elongation of those adhesions

At the end of the productive phase (after five days) the highest ultimate tensile strength was noted in the somatotropin group which was followed by the control and thyrotropin groups while the least force was required in the somatotropin plus thyrotropin group

In the collagen phase (after 14 days) paradoxically the highest tensile strength was obtained in the group with combined somatotropin and thyrotropin treatment The increase was considerable also in the thyrotropin group which left the control group behind The increase was least in the somatotropin group for which the lowest value was recorded at 14 days

2 The *cross section area* of the adhesions was studied by a planimetric method involving the weighing of paper cut outs

produced by the different methods one of the three quantities could be mathematically determined when the values of the other two were known

5 The granulation coming into existence around an injured tendon is subject to the same laws as the healing of a wound in general Hormones were concluded to have the following influence on the formation of granulation tissue

(a) Thyrotropin stimulated the productive phase of granulation formation

(b) Somatotropin promoted the collagen formation and caused rapid maturation of the granulation tissue

(c) Simultaneous administration of thyrotropin and somatotropin at first accelerated the production of granulations, at a later time collagen was formed in profusion

The material characteristic (apparent modulus of elasticity) occurring as coefficient in the expression which represents the force as a quantity proportional to the cross section area and elongation and inversely proportional to the length of the specimen under tension proved to be consistent with the collagen quantity A system has thus been established in which a given numericity can be assigned to the granulation tissue formed around an injured tendon

5 The results of the present studies are generally applicable to the behaviour of granulations under hormonal effect The following ultimate inferences seem justified in this respect

— Somatotropin causes maturation of the granulation tissue and accelerates the formation of collagen
— Thyrotropin stimulates the productive phase in the formation of new connective tissue
— Simultaneous administration of somatotropin and thyrotropin stimulates at first the production of granulation tissue and thereafter accelerates the collagen formation

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MOTION OF THE LUMBAR SPINE WITH SPECIAL REFERENCE TO THE STABILIZING EFFECT OF POSTERIOR FUSION

An experimental study
on autopsy specimens

by
SVANTE D. ROLANDER

GÖTEBORG 1966

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From the Department of Orthopaedic Surgery
University of Göteborg Sweden
(Head Professor Carl Hirsch)

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Foreword

The late Professor Eric Severin during the nineteen fifties was Head of the Orthopedic Clinic in Goteborg He was my respected chief, appreciated friend and teacher and aroused an interest in me in all those clinical problems that we, as orthopedic surgeons, constantly face
In 1961 Professor Carl Hirsch was appointed Head of the Orthopedic Clinic Sahlgrenska Hospital in Goteborg He introduced to me a completely new field of experimental work at the Biomechanics Laboratory This investigation was carried out under his guidance and I obtained the advantage of his extensive experience in experimental research and deep insight into the patho-physiology of the spine I wish to express my gratitude for his encouragement and never failing enthusiasm and for all the time he has willingly proffered
The solidarity and concern, characteristic of the members of our Clinic created a stimulating atmosphere for scientific work For this I want to express my appreciation to my colleagues and all the personnel and I would especially like to thank Docent Alf Nachemson M D, who put his method for measuring pressure and his personal experience at my disposal
During the passage of time problems often arose necessiting the cooperation of other institutions My gratitude is extended to Professors Jan Mellgren and Stig Ranstrom of the Department of Pathology Professor Bo Eric Ingelmark and Docent Thord Lewin M D of the Anatomy Institute Docent Sven Scheller M D of the Department of Roentgenology At Chalmer s Institute of Technology University of Goteborg I wish to thank Docent Allan Persson Techn D Division of Strength of Materials for constructive criticism and aid in the field of theoretical mechanics and Lector Sture Holm Techn lic Division of Statistic Analysis for his statistical supervision For the design and manufacture of experimental devices Instrumentmakers Axel Ericsson Goteborg the Elema Schonander Co Goteborg the Kifa Co Goteborg the Skefko Ballbearing Co (SKF) Goteborg the Swedish Electronics Consultants Goteborg and the Workshop of the Orthopedic Clinic Sahlgrenska Hospital Goteborg

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Goteborg in August 1966
Svante Rolander

Contents

I Introduction

When Eduard Albert introduced arthrodesis (*arthron* a joint *desis* binding together) in 1882 he unquestionably provided orthopaedics with a valuable *method of treatment*

The same principle of eliminating function by achieving a bony union between vertebral segments was presented in 1886 by Wilkins

Since that time the fixation of vertebral segments (spondylodesis an chylosing operation of the spine grafting of the spine, fusion) has been a much used surgical treatment The operation was applied early to tuberculous spondylitis and vertebral fractures Subsequently the indications *were extended to comprise various types of deformities and states of pain* which it was held were induced by mechanical disturbances in the mobile junctions between vertebrae

The manner of performing the operation has been gradually modified the aim being to arrive at the technique which would be most likely to ensure a bony union The resultant mechanical stability has been questioned from time to time but, as a rule healed fusion has been regarded *as synonymous with a good clinical result Considerable attention has* been paid to the healing of the spinal graft whereas little has been done to investigate the fusion s mechanical efficiency

Part of the difficulty in developing a surgical technique for spinal fusion is that the movements between two vertebrae involve three elements the disc and the two intervertebral joints The surgeon is thus faced with the choice of either attempting to fuse the posterior elements to a greater or lesser extent (posterior fusion) or, by excision of the disc, attempt to establish a direct connection between the vertebrae (interbody fusion) There are advantages and disadvantages with both methods In relation to the disc dorsal fusion is an extraarticular spondylodesis and its mechanical potential for relieving the disc has been called in question Consequently the fusion has come to include more and more of the vertebral arches i e the spinous articular and transverse processes The attraction of interbody fusion on the other hand is that it both permits extirpation of disc tissue which has been regarded as the site of pathological changes and provides large areas of spongy substance for the fusion

Discussion concerning the choice of method has concentrated upon the complications presented by imperfect healing and also upon failure to relieve pain

In the present study, experiments have been conducted on autopsy specimens from the lumbar spine The idea was to study how vertebrae move in relation to one another when loaded vertically and also to assess the stabilizing effect of various types of dorsal fusion.

The purpose of the experiments was to develop a method for simulating posterior lumbar fusion in accordance with a number of the principle techniques and to investigate the effect of vertical loading Equipment was designed for measuring and registering deformations in vertebrae and discs, with comparisons under identical loading conditions between intact specimens and the same specimens subjected to simulated fusion or some other alteration By applying eccentric loads, the vertebral segment could be made to adopt positions of equilibrium corresponding to extension, flexion and lateral bending

During the loading experiments, recordings were made of the intradiscal pressure as well as of the deformations which arose in and between the various parts of the vertebrae. The mathematical units expressing the force applied and the deformations measured have been selected with a view to facilitating comparisons between specimens from different individuals

II Revue of literature

Development of fusion operations

Surgical technique

In the first operations to stabilize the spine wires were looped around laminae and spinous processes (Wilkins, 1886, Hadra 1891 Chipault (1900) On the grounds that the wire loops could not cope with the mechanical strains in the spine, Lange 1910—1911 preferred to fit steel rods paraspinally, a method which he tried out for several years in animal experiments as well as clinically on man

Then, in 1911, several methods were reported for bridging posterior parts of the vertebral arch with bone In Albee s operation a tibial graft is inserted into a split in the spinous processes Henle advocated placing a tibial graft on either side of the spinous processes (paraspinally) considering it an advantage that the laminae are thereby included in the bony union Similar methods were described by Whitman (1911) and de Quervain (1912) A somewhat different principle involved division of the spinous processes and downward fracture of bony flaps to interdigitate between the laminae below (Hibbs 1911)

Numerous modifications and combinations of these methods were published during the next few years one of which involved fusion between laminae by chiselling out the base of the spinous process and inserting a tibial graft (Halstead, 1915) Hibbs (1918) extended his method to include arthrodesis of the intervertebral joints by curettage of the joint cartilage Fixation of the primary graft was improved by resecting the spinous processes and downward fracture of bony flaps to interdigitate between the adjacent healthy spinous proces es (Waygiel, 1922) Having resected the base of the spinous process, the tibial graft could be embedded in the laminae (Calvé & Galland 1920) A further development was to shape the tibial graft like a fish tail or clothes pin to fit in between the spinous processes (Gibson, 1931) Similarly a massive H shaped graft was taken from the ilium and reinforced with iliac strips to include the intervertebral joints (Bosworth 1942 1945 1952) a technique which has been applied by several authors (Blount, 1942 Breck & Basom, 1943)

The importance of widening the intervertebral space dorsally has been emphasised (e.g Bosworth, 1942 Breck & Basom 1943, McBride, 1949), the last of these authors using a mortised transfacet bone block ' in order to achieve a primary stability that will permit early mobilisation of the patient Other means which have been tried to this end are screws through the articular facets (King 1948) a paraspinal metal plate and matching graft (Straub 1949 Wilson & Straub, 1952) and double metal plates fixed by bolts and nuts through the spinal processes (Williams 1950)

Combined lumbosacral and sacro-iliac fusion has been recommended by several writers (Smith Petersen 1924, Chandler, 1929, Campbell, 1930) In a modification of Hibbs technique, transplants were placed between the transverse processes (Mathieau & Demirleau, 1936, Watkins, 1953 Adkins 1955 Truchly & Thompson, 1962 Wiltse 1964)

A method for interbody fusion was published in 1936 by Mercer who had tried it out in two cases using a dorsal approach the dorsal part of the disc and the adjacent vertebral surfaces are resected and two iliac transplants are wedged into the space thereby created (This method has subsequently been adopted by Owens & Williams, 1945, Jaslow 1946 James & Nisbeth 1953 Cloward, 1953 DuToit, Domisse & Muller, 1956 Domisse 1959)

As early as 1923 tuberculous spondylitis was treated with radical resection from a transabdominal approach and tibial grafts in the defect (cf Ito, Tsuchia & Asami, 1934) This method has recently been advocated by Fellander (1955 1965) and Stock (1962)

Another proposal for interbody arthrodesis with a ventral approach called for a tibial graft in a borehole through the 5th lumbar to the 1st sacral vertebra (Capener 1932) This was put into practice by Burns (1933) Jenkins (1936) Speed (1938) and Friberg (1939) A similar fixation has been obtained with two fibular grafts and a screw introduced prismatically in different planes (Henschen, 1942) and with three flanged nails (Ramser 1943) Another method involves radical excision of the disc from a ventral transperitoneal approach and its replacement with a U-shaped heterologous transplant, which is kept in place with vertical grafts (Lane & Moore 1948) This method has been further developed (Harmon 1959 1962 Sacks 1962, 1965 Raney and Adams, 1962)

Very good results have been reported for a combination of interbody and posterior fusion in one session (Harmon 1963)

In this development of surgical techniques there is a trend towards increasingly massive fusions incorporating more and more of the two vertebrae Although the reasons behind the modifications are not always stated explicitely the primary aim has presumably been to achieve greater

mechanical stability and thereby ensure healing and improve the clinical result In principle, four surgical techniques have emerged

1 Bony union between spinal processes (Albee Henle and others)
2 Fusion including arches and intervertebral joints (Hibbs Bosworth and others)
3 Fusion comprising the entire vertebral arch, i e including the transverse processes (Mathieau & Demirleau Boucher & Vancouver Watkins Wiltse and others)
4 Interbody fusion from dorsal (Mercer Cloward) or ventral approach (Lane & More Harmon and others)

Special indications for fusion

Tuberculous spondylitis

In the early years of this century fusion was chiefly used for tuberculous spondylitis and to some extent for vertebral fractures i e conditions with defects in the supporting bony structure and a danger of progressive spinal deformities In such cases the graft had to be able to carry practically the entire load placed upon the spine particularly after forced reduction as proposed by Calot (1905) Successive correction over a long period (Waldenstrom 1924) followed by surgical grafting in a quiet phase was reported to give good results Yet as Biesalski (1923) points out in spite of the favourable reports from America many surgeons in Germany rejected surgical grafting for tuberculous spondylitis Biesalski believed that opinions differed so widely because the operation was per formed without fixed indications He considers that one cannot both unload and fix the spine but only achieve a certain compromise The only way of demonstrating the effect of a grafting operation according to Bachlechner (1921) is by post mortem studies Taking a specimen from a 5 year old boy who had died of miliary tuberculosis 8 weeks after the operation, he showed that the graft formed a firm union With the transverse process of T 11 placed against the articular process of T 12 all flexion was prevented and the graft was subject to traction only not to flexion forces Investigating ten specimens partly healed and partly resorbed after fusion according to Albee or Henle Biesalski (1923) found that in no case had the graft grown longer or broader and was in many instances wafer thin Roeren (1924) questioned the use of a graft, since it prevents contact and spontaneous union between the vertebral bodies He allowed that the graft may be well suited to carry bending forces in the

sagittal plane, but doubted whether this was equally true for rotation about the longitudinal axis He preferred Hibbs method arguing that fusion according to Albee made a lever too long in relation to the static force The nearer the fusion approximates the vertebral body the sooner it is able to fullfill its task The same objections have been made by Whitman (1911) Bachlechner (1921) and Hoffman (1925) According to *Henle (1926) the technique developed by Halstead (1915)* has the disadvantage that the graft has its smallest cross section in the frontal plane and is thus inferior to a paraspinal graft in preventing flexion and extension Lange s original site for the metal rods was criticised by v Baeyer (1922), however as being too close to the segment s axis consequently *he shaped celluloid rods to fit against the apex of the spinous* process

Most authors at this time recommend that fusion for spondylitis should include at least one healthy vertebra on each side of the affected segment Along with Roeren, however Calvé & Galland (1920, 1936) stress the importance of direct contact between the vertebral bodies, they favour a short fusion — involving diseased vertebrae only and without any correction The gibbus thereby can be compensated in adjacent healthy segments They place the graft as far ventrally as possible and anchylose or chisel off the intervertebral joints, which serve as a fulcrum for the deformity On the basis of 23 operated cases of spondylitis and an autopsy specimen Joisten (1929) concluded that the fusion unable to withstand the deforming forces, had been transformed to correspond to the healed kyphosis so that his patients could have been spared the operation Of the 76 orthopaedic surgeons in Europe who answered a questionnaire Schmieden (1930) *found that 8 supported the method (Henle Albee)* 38 in isolated cased 17 were not interested and 13 were definitely opposed

It is said that dorsal fusion does not accelerate bony union between the vertebral bodies by means of ventral growth and depends entirely upon the type of infection focus *(Puig Guri 1947) Union is achieved soonest* with a focus close to the edges of the bodies it never takes less than a year to form however and is seldom complete in under 3-4 years

In an X ray examination of 507 cases of operated spondylitis Alvik (1949) detected mobility (max 9°) even though fusion had been achieved without complications involving the graft *He ascribed this mobility to* the elasticity of the graft spinous process and arches arguing that for complete stability the fusion must include as much of the posterior segment as possible

A study has been made of all the cases of spondylitis which have been

operated upon at the New York Orthopaedic Hospital, — 1 009 cases up to 1947 (Hallock & Jones 1954) 210 patients operated upon from 1911—1915 were previously studied by Hibbs (1918) 286 patients operated upon from 1915—1920 were reported by Hibbs & Risser (1928) Swift (1940) reported on 817 cases operated upon from 1918—1930 The presence of solid fusion may not prevent increasing spinal deformity The amount of the deformity was directly proportional to the degree of destruction of the vertebral bodies In none of the patients did the fusion hold apart the diseased vertebrae for a prolonged period of time

Having used dorsal fusion for tuberculous spondylitis up to 1955 Stock (1962) found the results far from satisfactory Consequently 418 cases were treated in 1955—60 by radical extirpation and interbody fusion using a ventral approach It did not take long for the fusion to become stable, and the patient could be allowed up even earlier, since the load on the spine stimulated hypertrophy of the graft and accelerated healing Only 17 per cent of the results were good with dorsal fusion (cf Cleveland 55 per cent and Swett less than 40 per cent) whereas interbody fusion produced a solid union in 90—95 per cent.

Fractures

The considerations governing surgery for fractures of the spine have been much the same as those for spondylitis There is a tendency to functional treatment of stable fractures with early mobilisation, while surgery is considered for unstable fractures (liable to dislocate) It has been argued that unstable fractures should in principle be protected until spontaneous anterior fusion develops (Nicoll 1949) out of ten miners with unstable dislocated fractures treated conservatively seven made a complete recovery whereas none of those undergoing arthrodesis returned to a coal face job posterior fusion is mechanically less sound because the graft is under tension instead of compression Watson Jones (1955) agrees with Nicoll that the ideal end result is solid fusion but notes that, as this takes several years to achieve and the patient is an invalid during this period rehabilitation becomes a serious problem He therefore prefers early dorsal fusion according to Hibbs, including the intervertebral joints and with additional crista bone chips Spinal metal plates have been reported to be safe and effective (Holdsworth & Hardy 1953) and to arrest the development of a gibbus (Pennybacker 1953 Dick, 1953) Subsequently, however, it has been shown that metal plates do not prevent gibbus as witnessed by the finding of loosened plates screws and bolts, while several cases with post-operative progressive nerve symptoms suggest that the method cannot be regarded as safe (Guttman, 1959)

Spondylolisthesis

During the Twenties and the Thirties special attention was paid to anomalies and deformities in the lumbosacral angle (Johanson, 1920, Willis, 1924 1941, Schamburow 1926 Wiles, 1935, Kimberley, 1937) and in particular spondylolisthesis Rayerson (1932) reports that he operated on the first case of spondylolisthesis in 1911 Albee (1927) reports that without exception, the results were most gratifying in the eight cases in which he employed his operation for spondylolisthesis The latter s report, however is described as summary and unconvincing by Mouchet & Roederer (1927) who ask how this dorsal graft can ensure fusion in cases of spondylolisthesis where the dislocation affects the vertebral body and suggest placing the graft between the articular processes of the adjacent inferior and superior vertebrae Salmon & Contiadés (1933) believe that once dislocation has started it is almost bound to continue owing to the body weight and the oblique position of the sacrum, the operation should aim at changing the line of force from the superimposed body weight and preventing luxation of L 5 They consider that the transplant meets these requirements indirectly by carrying part of the body weight behind the laminae from L 3 — S 1 Albee s method is criticised for inferior adaptation to pronounced lordosis and a poor attachment to the sacrum They find it logical to try to fix the spine as close to the centre of gravity as possible (according to Campbell and Lance & Aurousseau) but consider that the technique is too difficult instead, they recommend bilateral paraspinal grafting according to Henle

Arguing that a dorsal transplant has an insufficient mechanical efficiency in spondylolisthesis Capener (1932) proposed direct fixation of the displaced vertebral body This started the development of interbody fusion (Burns 1933 Mercer 1936 Jenkins 1936 Friberg 1939 Gjessing 1951, d Aubigne 1952, Laurent 1958) Friberg (1939) questioned the justification for placing the transplant far ventrally', since this gives it a shorter lever He points out that an arthrodesis in the intervertebral joints cannot prevent slipping in spondylolisthesis because it does not affect the slipped anterior fragment However he also demonstrates that slipping does not occur in the adult so that surgery on this indication cannot be justified except possibly for children His investigation showed that the pain easing effect is only slightly greater for surgical than for conservative treatment No parallelism between the roentgen anatomic and functional results has been seen good functional results were observed when the transplants were fractured or resorbed and poor results when the grafts were well fused In adults the effect of the Albee graft is not due to its taking on any of the body weight or to its preventing

the slipping (since slipping does not occur) but in its producing an extraarticular arthrodesis on the intervertebral joints On the basis of 50 cases of spondylolisthesis in the age range 5—20 years and 110 operated cases over 20 years of age Taillard (1955) concluded that the transplant cannot prevent slipping or mobility in the segment but that a bony union does have a good effect on the pain Young girls with a pronounced wedge shaped L 5 and a convex sacral base are liable to progressive slipping which would justify anterior fusion in such cases Discouraging results with dorsal transplants and metal plates for spondylolisthesis have been reported by d Aubigné (1952) who considered it more logical to undertake interbody fusion and reported good functional results with a transperitoneal approach in 16 cases In one out of five cases of ventral fusion Sicard (1952) accidentally penetrated the cauda equina with a screw, causing neurological disorders he argues that since dorsal fusion gives good results young people with a purely functional condition should not be exposed to the risk inherent in ventral fusion A modified operation for spondylolisthesis has been developed by Marino Zucco (described by Montiselli & Maresca 1957) The loose arch is temporarily removed the superior and inferior facets are denuded of cartilage and the pseudoarthrosis is excised Costal strip are placed between the intervertebral joints and the loose arch is refixed with short screws through both transplant and facet Boucher & Vancouver (1959) recommend fixation with long screws pointing ventrally distally and laterally so that they penetrate the vertebral body and the alae of the ilium respectively via the pedicles

Chaklin (1937) used a paravertebral approach for interbody fusion in 6 cases of spondylolisthesis Hirsch (1966) has described a method for ventral extradiscal bridging from L 5 to the sacrum used successfully on 3 young girls with pronounced slipping

A few cases of spondylolisthesis have been successfully reduced but subsequently became dislocated again in spite of fusion (Watson Jones 1938 Friberg 1939) Treatment by open reduction and interbody osteosynthesis has been reported in 6 cases (Denecke 1957) The sacrum was exposed from a dorsal incision and from an incision between the rectum and sacrum the disc was extirpated together with a wedge shaped segment of the sacrum and L 5 after which L 5 was forced into place with a special clamp and fixed with two screws from S 2 to L 3 This method met with considerable opposition on the grounds that the extent and risks of the operation were out of proportion to the patient s disorder (Erlacher 1957)

Spondylolisthesis

During the Twenties and the Thirties special attention was paid to anomalies and deformities in the lumbosacral angle (Johanson, 1920 Willis, 1924 1941 Schamburow 1926, *Wiles, 1935 Kimberley 1937*) and in particular spondylolisthesis Rayerson (1932) reports that he operated on the first case of spondylolisthesis in 1911 Albee (1927) reports that without exception the results were most gratifying in the eight cases in which he employed his operation for spondylolisthesis. The latter s report however is described as summary and unconvincing by Mouchet & Roederer (1927) who ask how this dorsal graft can ensure fusion in cases of spondylolisthesis where the dislocation affects the vertebral body and suggest placing the graft between the articular processes of the adjacent inferior and superior vertebrae Salmon & Contiades (1933) believe that once dislocation has started it is almost bound to continue owing to the body weight and the oblique position of the sacrum the operation should aim at changing the line of force from the superimposed body weight and *preventing luxation of L 5 They consider that the transplant meets* these requirements indirectly by carrying part of the body weight behind the laminae from L 3 — S 1 Albee s method is criticised for inferior adaptation to pronounced lordosis and a poor attachment to the sacrum They find it logical to try to fix the spine as close to the centre of gravity as possible (according to Campbell and Lance & Aurousseau) but consider that the technique is too difficult instead they recommend bilateral paraspinal grafting according to Henle

Arguing that a dorsal transplant has an insufficient mechanical efficiency in spondylolisthesis Capener (1932) proposed direct fixation of the displaced vertebral body This started the development of interbody fusion (Burns 1933 Mercer 1936 Jenkins 1936 Friberg, 1939 Gjessing 1951 d Aubigne 1952 Laurent 1958) Friberg (1939) questioned the justification for placing the transplant far ventrally , since this gives it a shorter lever He points out that an arthrodesis in the intervertebral joints cannot prevent slipping in spondylolisthesis because it does not affect *the slipped anterior fragment However,* he also demonstrates that slipping does not occur in the adult so that surgery on this indication cannot be justified except possibly for children His investigation showed that the pain easing effect is only slightly greater for surgical than for conservative treatment No parallelism between the roentgen anatomic and functional results has been seen good functional results were observed when the transplants were fractured or resorbed and poor results when the grafts were well fused In adults the effect of the Albee graft is not due to its taking on any of the body weight or to its preventing

To be truly strong the fusion area should extend from the cartilaginous cap of one transverse process across to the cartilaginous cap of the other and should extend anteriorly to include the articular facets This rod of bone must be of sufficient diameter to resist bending forces that produce stress fractures months or years later According to Blount, the treatment of scoliosis cannot be regarded as satisfactory until pseudoarthrosis has been almost entirely eliminated Blount et al (1958) hold that surgery is indicated for progressive scoliosis irrespective of age Although fusion in children admittedly inhibits growth this is preferable to the effects of progressive gibbus They have not noted any significant increase of the scoliosis after fusion

Low back pain

Even before the spread of disc surgery in the nineteen thirties (Mixter & Barr 1934) good results were reported with lumbar fusion for low back pain with or without sciatica In many cases, the back pain was attributed to some congenital defect or anomaly demonstrated by roentgenography and held to cause lumbosacral instability (Johanson 1920 Schamburow 1926 Chandler 1929 Hibbs & Swift, 1929 Ferguson 1934 Wagner 1935 Kimberley 1937)

It was emphasised that fusion may be indicated for persistent back pain even though the X ray findings may be negative (Schamburow 1926) Williams & Yglesias (1933) held that a lowered interspace causes subluxation in the intervertebral joints and constriction in the foramina the nerve is pressed against the facets eliciting pain which increases with movement They accordingly recommend fusion and if the sciatica persists facetectomy Ghormley (1933) pointed out that arthritic changes are common in the intervertebral joints and are presumably bound to elicit discomfort in the same way as in other articulations, i e aching pain on movement, swelling and fixation He argued that the lumbosacral facets which are positioned to prevent ventral displacement, are particularly exposed to continuous strain in their role as stabilisers of the spine His recommendation is fusion according to Hibbs Asymmetric facets as a cause of lumbosacral pain with or without sciatica has been discussed by Goldthwaith (1911) Danforth (1925) Putti (1927) Brailsford (1928—1929) Ayers (1935) and Key (1948) Chandler (1929) noted that, after fusion sciatica disappeared to a lesser extent than did back pain. During a wave of enthusiasm practically all low back pain with and without sciatica was attributed to prolapse of a disc (Dandy 1941 1944 Young & Burns 1951 and others) It was found however that the back pain often persisted with a higher frequency than the sciatica after simple

extirpation of the disc [Briggs & Milligan (1944) Friberg & Hirsch (1946), Ghormley (1957) Hirsch & Nachemson (1963)] and fusion was once again considered Persistent back pain was reported in 38 5 per cent of 217 disc operations at the Mayo Clinic and fusion was recommended as a secondary measure in special cases (Love 1947) Friberg & Hirsch (1946) note that disc degeneration is a common condition which is only occasionally complicated by prolapse Surgery for a prolapsed disc simply means that the pressure on the root is removed while the pathological changes in the disc are left unchanged They noted a 30 per cent incidence of persistent spinal ailments and recommended fusion as a secondary procedure for persistent back pains or as a primary measure for severe lumbago with a negative myelogram and exploration Armstrong (1958) writes that in theory, it would be best to perform arthrodesis immediately in all cases as a combined operation, but adds that demonstrative better results than those following simple removal of the nucleus cannot be supported by the published results of operated series In fact, the results of extirpation of the nucleus combined with immediate arthrodesis seem to be if anything a little worse than those produced by simple removal of the diseased nucleus Consequently Armstrong reserves fusion for a late and second stage procedure in selected patients A combined operation produced good results in only 14 per cent of the cases in an insurance company's records (Marble & Bishop, 1945) Bony union was achieved in only a few out of 100 cases of dorsal interbody fusion but the clinical results were held to justify the method (Du Toit, Domisse & Muller, 1956) Out of 50 patients undergoing lumbosacral fusion, 14 had boney union and 8 were pleased with the result (Attenborough, 1955) Bony fusion has been said to result in such complete immobilisation that prolapse of a disc cannot occur within the fusion (Ghormley, 1933 Dandy 1944 Unander Scharin 1950 Cloward, 1953) Yet prolapse of a disc after bony fusion has been described by several writers (Love 1947 Hensell 1958)

Pseudoarthrosis

In practice the only way of assessing osseous union after surgical fusion is by X-ray examination Some uncertainty remains however even after functional tests with flexion extension and lateral flexion (Kimberley 1957 Bosworth 1945, 1952 Carr & Hyatt, 1955 McBride & Shorbe 1958 Domisse 1959 Overton 1959) A definite assessment can be made only by exploration Smith 1923 Jónsson, 1953 Watkins, 1953 1959 Thompson & Ralston 1949 Rolander 1964)

Table 1 *Pseudoarthrosis in fusion of L 4 — S 1*

Author	No of operations	Technique	Incidence of non union (per cent)
Kimberley (1937)	93	Hibbs	31 2
Cleveland, Bosworth & Thompson (1948)	357	H graft	17 4
Thompson & Rals on (1949)	169	Hibbs	23 6
Thompson & Ralston (1949)	40	Transfacet screws	55 1
Straub (1949)	80	Wilson s plate and cortical graft	14
Unander—Scharin 1950 b	80	Posterior, various methods	27,5
Unander—Scharin 1950 b	18	H graft	5 6
Unander—Scharin 1950 b	7	Albee	88 9
Smith 1952	123	Hibbs	26
Watkins (1953)	10	Posterolateral block	20
Hellstadius (1954)	57	H graft	27
Shaw & Taylor (1956)	55	Only cortical	36
McBride & Shorbe (1958)	77	Facet block	36
Truchly & Thompson (1961)	41	Posterolateral, slivers	7 3
Howorth (1964)	33	Hibbs+screws through the facets	36

There is a wide variation between reports concerning the risk of pseudoarthrosis as assessed from clinical follow up examinations Yet without bony union the clinical result in the form of relief from pain is often relatively good According to Cleveland Bosworth & Thompson (1948) 42 per cent of the patients had no pain in spite of pseudoarthrosis while 5 per cent had persistent pain notwithstanding a bony union Reporting 103 cases of fusion according to Chandler (1929), Newman (1955) found that 88 per cent of those with bony union had good clinical results compared with 53 per cent of those with pseudoarthrosis Shaw & Taylor (1956) had good clinical results in 77 per cent of cases with pseudoarthrosis Good results in 97 per cent of cases with bony union and in 67 per cent of those with pseudoarthrosis are reported by Eie (1964) Unander Scharin (1950) reports graft complications in 21 per cent of the cured cases At re operation for suspected pseudoarthrosis Thompson & Ralston (1949) found bony union in 8 out of 59 cases Rovig (1949) reported 7 healed fusions in a group of 11 reoperated patients Rolander (1964) found 10 cases of bony union among 35 fusions of L 4 — L 5 — S 1

re operated for persistent ailments Lange (1959) noted bony union with varying clinical results in 20 per cent out of 99 cases

The frequency of pseudoarthrosis is consistently reported to be lower for fusion of the lumbosacral segment only than for extensive fusion In a series of 230 cases, pseudoarthrosis was detected roentgenologically in 8 4 per cent of the fusions involving one segment as against 24 3 per cent of the two segment fusions (Smith, 1952) For 251 cases with the facet block technique McBride & Shorbe (1958) report figures of 9 5 and 36 per cent respectively Bosworth (1952) reported that pseudarthrosis occurred in 3 8 per cent of 79 cases of fusion of L 5 — S 1 with an H graft, 11 2 per cent in 223 cases of fusion of L 4 — S 1 and 45 5 per cent of 11 cases of fusion of L 3 — S 1

Adkins (1955) writes that he has tried a variety of surgical techniques with discouraging results Dorsal interbody fusion appealed to him most in theory and he performed a series of 70 operations but found bony arthrodesis in only one case A similar experience has been reported by McBride & Shorbe (1958)

Spondylolisthesis has been described as a complication of dorsal fusion (Unander Scharin, 1950 a Andersson, 1956, Harris & Wiley, 1963)

Clinical results following fusion

In order to make an objective assessment of the clinical effect of a method of treatment, comparisons must be made with an equivalent group of patients treated with some other method or left untreated Comprehensive studies along these lines are lacking for lumbago Attempts have however been made to select comparable groups retrospectively Farrel & McCracken (1941) studied the case reports for a series of patients treated with fusion during the years 1914—40 and selected those for which the data suggested the diagnosis of a prolapsed disc this group was then compared with one treated later with combined extirpation of the prolapsed disc and fusion There was no clear difference between the results Another study concerned 503 patients from 1939—47 with the clinical diagnosis of prolapsed disc (Millikan 1954) the prolapse was extirpated in 329 cases and 100 received conservative treatment No difference was found in the end results Surgery was suggested as a selective treatment for patients with progressive paresis and for those with continuous or intermittent attacks that are not affected by conservative therapy Similarly Soderberg (1956) made a retrospective selection of 92 patients who if treated more recently, would certainly have been recommended

for operation on a prolapsed disc This group was compared with a later series in which the diagnosis of prolapsed disc was confirmed at operation and treated with simple extirpation Here too, there was no definite difference between the long term results An impartial study by a research committe of the American Orthopaedic Association (Nachlas 1952) concerned 918 patients who had been operated on for back ailments in various parts of the U S A during the period 1941—46 Of the patients available for a follow up examination, 256 (group A) had been treated with simple extirpation of the prolapsed disc and 118 (group B) with a combined operation The result was considered satisfactory for 59 80 per cent in group A and for 69 77 per cent in group B The 10 per cent difference in satisfactory results is thus based upon selected material with a follow up of less than half of the individuals In a study of 1,176 cases with a simple (84 8 per cent) or a combined (15 2 per cent) operation, Gurdjian et al (1961) report excellent or good results for 67 per cent of both groups Young & Love (1959) found that the results of a combined operation were 20 per cent better than with simple disc extirpation but they point out that the difference is not statistically significant

General indications for fusion

Indications for lumbar osteosynthesis have been reported by Poppem (1945) primary fusion in prolapsed disc with predominant back ail ments for signs of spinal instability, abnormal facets and particularly if the patient does heavy work Platt (1948) recommends primary fusion at disc operation with a long history of back ache in patients with strenuous work Pouyanne (1951) lists displaced vertebrae limited arthros is dissatisfactory results after disc operation old and rebellious lumbar pain, and as a precaution in hard workers Wilson & Straub (1952) gives spondylolisthesis disc prolapse congenital anomolies osteo arthritis insta bility spinal fractures Humphries Hawk & Berndt (1957) lumbar disc degeneration with disabling back pain precipitated by movement of the back and relieved by a supporting brace or by lying down Morgan (1957) considers that primary instability is the most common cause of low back pain and usually indicates fusion Newman (1959) instability and localised severe degeneration in a disc or intervertebral joint Truchly & Thompson (1962) primary and secondary instability Howorth (1963) considers that fusion is indicated when there is instability or anomalies in the lumbosacral region with disabling pain unrelieved by adequate

conservative measures Overton (1959) has summarised the indications for fusion as follows One basic requisite for a candidate for fusion is the presence of some mechanical derangement in the area of the spine to be fused

Anatomical and physiological considerations

The conditions for stabilising a ligamentous lumbar spine are determined by the anatomical design and the mechanical properties of the intervertebral discs, the various parts of the vertebrae and the material for osteosynthesis For the descriptive and functional anatomy the reader is referred to the appropriate textbooks (e g Fick 1904, Strasser, 1913, Braus, 1921, Rauber & Kopsch, 1920 Gray, 1962)

A motion segment (Junghanns, 1931) consists of two vertebrae and the intervertebral disc and ligaments between these The vertebral body has a slightly concave silhouette and its horizontal section is usually shaped like a kidney When studying physical properties, it should be noted that the cortical layer of the body is strikingly thin and pierced, particularly dorsally, by several nutrient foramina The body s cranial and caudal surfaces are formed of concave, bony endplates The border serves as a cortical reinforcement for the attachment of the end plate to the periphery of the body it is thickest ventrally and laterally, becoming narrower dorsally The hyaline end plate delimits the disc from the body of the vertebra

The annulus is made up of concentric layers of collagenous fibres running helicoidally from one vertebral body to the next in such a way that the fibres in contiguous laminae lie at about 100° to each other (Horton 1958, Naylor 1962 Galante & Hirsch, 1966) The fibres in the outer zone attach like Sharpey s fibre to the border of the vertebral body while in the inner zone, they are joined to the hyaline cartilage (Hirsch & Schajowicz 1952) The collagenous fibres which correspond to those in fascia and tendon tissue are extremely strong and not very extensible (McMaster, 1933, Verzár, 1957 1963) In the lumbar spine the annulus fibrosus is higher and thicker in front than behind (Todd & Pyle, 1928 Joplin 1935 Inman & Saunders, 1947) As a result, the centre of the nucleus pulposus lies somewhat dorsal to the geometric centre of the disc (Schmorl 1927 Bohmig 1931) The nucleus pulposus or inner core of the disc consists of a three-dimensional network of collagen fibrils enmeshed in a mucoprotein gel which contains various mucopolysaccharides (Hirsch Paulson Sylvén & Snellman, 1951, Happey, MacRae &

Naylor 1953 Naylor, 1962) It occupies about 30—50 per cent of the disc s area of cross section (Perey 1957, Nachemson 1960 Eie 1966) In sections from young individuals it protrudes above the cut surface of the disc This has been taken as a sign of an inner pressure (Fick, 1904 Joplin, 1935, and others), which has been considered of decisive importance for the hydro elastic function of the disc (Roux 1895 Calve & Galland 1930 Petter 1933 Joplin 1935 Charnley, 1952) The cavity in the centre of the nucleus normally measures less than 1 cm³ but becomes larger in degenerated discs (von Luschka 1856 1858 Schmorl, 1927 Tondury 1955 Fernstrom 1960 Abel & Harmon 1960 Teichert 1962a) which may spontaneously appear to be filled with gas i e the vacuum phenomenum at X ray examination (Magnusson 1937 Knutsson 1940 Teichert 1962 b) or be demonstrated by nucleography in vivo and on autopsy specimens (Hirsch 1948 Lindblom 1948 1951 Hult 1951 Romanus & Yden 1952 Nordlander, Salen & Unander Scharin 1958 Abel & Harmon, 1960 Fernstrom 1960 Teichert 1962 a) In young individuals the water content of the nucleus (approximately 80 per cent) is about *10 per cent higher than that of the annulus but the difference diminishes* with increasing age and in disc degeneration parallels a relative increase in the protein content (Puschel 1930 Sylven Hirsch Paulson and Snellman 1951 Naylor & Smare 1953 Bush, Horton Smare and Naylor 1956 Mitchell Hendry & Billewicz 1961 Naylor 1962)

The disc is covered ventrally by the anterior longitudinal ligament and dorsally by the thinner posterior longitudinal ligament The vertebral arches of the motion segments are connected by the arcuate ligaments the supraspinous interspinous and intertransverse ligaments The ligamentum flavum attaches to the ventral surface of the articular processes and articular capsules forming the dorsal limit of the vertebral canal It is chiefly composed of highly elastic fibres (according to Krafka the modulus of elasticity of collagen fibres is 300 times that of elastic) In the lumbar spine of the dog the extensibility of the ligamentum flavum is 63 per cent and its tensile strength is 671 g/mm² (Nunley 1958) When the ligamentum flavum is sectioned horizontally it contracts (both in vivo at surgery and in dissection specimens), indicating that the lumbar discs are subject to a prestress (Fick, 1904 Malmros 1942 Akerblom 1948 Nachemson 1960 Riga & Robacki, 1965)

The other ligaments mentioned above consist chiefly of interlacing layers of collagenous fibrils and serve together with the bony processes as attachments for the spinal muscles

The intervertebral joints are true diarthroses In the lumbar spine their surfaces are cylindrical set chiefly in the sagittal plane though usually

narrowing somewhat towards the back In front, the cranial facets enclose the caudal, thereby preventing ventral translation (horizontal displacement instability) of the upper vertebra in each pair (McNab 1950, Lewin, 1964) Otherwise the joints are designed to permit a relatively considerable degree of rotation around the sagittal and frontal and vertical axes (Guntz 1934 Lewin, 1964, 1965) Like the intervertebral discs, the intervertebral joints are frequently the site of degenerative processes, which is one of the reasons why their load bearing function has been discussed (Guntz 1934 Shore, 1935 Severin, 1943, Gianturco, 1944, Ingelmark 1956 Kelly, 1958, Lewin 1964) In general it has been considered that the intervertebral joints serve as guides for the motion segment (Fick 1904 Keyes & Compere, 1932 Armstrong, 1958 Nachemson 1963)

The nucleus pulposus has been reported to act as a fulcrum for the segment's rotation (Fick 1904 Steindler, 1955), which has an inconstant (momentary) axis of movement normally centering on the nucleus (Dittmar 1930) but displaced towards the intervertebral joints in disc degeneration (Gianturco, 1944, McNab, 1950)

Nutrition and innervation of the vertebral body and disc

The vertebral body is supplied by two arteries, which run laterally and backwards midway down the body of the vertebra, through the intervertebral foramen and enter the dorsal aspect of the body There are small caudad and cephalad periostal branches while larger branches are given off to the articular capsule and vertebral arch (Hanson, 1926) Numerous capillaries run under the end plate of the vertebral body with branches perpendicular to it (Virgin 1958, Wiley & Trueta 1959)

In the embryo, the nucleus is supplied by a central axial artery running vertically from the os cous vertebra to the cartilaginous plate There are also marginal vessels dorsally and ventrally (Bohmig, 1931 Hirsch & Schajowicz 1952 Mineiro 1965) which anastomose with one another and with the perichondral capillery system (Obermuth 1930) The vessels become obliterated in the growing child leaving scars in the hyaline end plate

'The nucleus pulposus and the annulus fibrosus are completely without vessels during every phase of the individual's adult life' (Hirsch & Schajowicz 1952) In the outer layers of the ligaments there are a few small vessels but these do not penetrate the annulus

The innervation of the lumbar segment is provided by the meningeal branch which runs recurrently through the intervertebral foramen and divides into a cephalad and a caudad branch behind the pedicle supplying the ligaments and periostium as well as providing peri

vascular branches to the epidural region and dura mater Posterior branches run to the transverse process and articular processes as well as along the arch to the interspinous ligament (Pedersen Blunk & Gardner 1956) Tsukada (1938) reported neural elements in both the annulus fibrosus and the nucleus pulposus while Roofe (1940) found them in the outer layer of the annulus fibrosus Most studies however confirm the presence of nerves in the longitudinal ligament but not in the annulus (Keyes & Compere, 1932 Coventry Ghormley & Kernohan 1945 Wi berg 1949 Hirsch & Schajowicz, 1952 Mulligan 1957 Jackson 1966) Implantation of nucleus tissue in the rabbit produces an auto immune response (Bobechko & Hirsch 1965) with local inflammatory reaction. Rupture of the annulus fibrosus often leads to the formation of granulation tissue or fibrous connective tissue (Andrae 1929 Eckert & Decker 1947 Lindahl & Rexed 1951) this can result in secondary vascularisation of *the disc and might permit the ingrowth of accompanying nerves* (Hirsch & Schajowicz 1952)

Following improvements in staining techniques the presence of sensible nerve endings in the peripheral parts of the annulus has been verified by Hirsch Ingelmark & Miller (1963) using intravital methylene blue and by Jackson (1966) with cholinesterase and silver impregnation Miller was also able to demonstrate nerve endings between the trabeculae of spongy bone Milgram & Robinson (1966) showed nerve endings in the Haversian system of cortical bone According to Jackson (1966) the cartilaginous end plates of the vertebral bodies are accompanied by nerves terminating in very thin branches and frequently *forming open loops in* the vascular channels of the cartilage plates This may be of special interest in view of the frequent and early occurrence of degenerative foci located in the greatest concavity of the end plate (e g Übermuth 1930 Coventry Ghormley & Kernohan 1945 Tondury 1955)

Previous studies of mobility and stability in the lumbar spine

Studies of motion utilizing cadavers

The mobility of the spine has been repeatedly studied by means of *measurements on cadavers ever since the time of Galen (for an extensive* review see Andersson & Ekstrom 1940-41)

The initial position for measurements has been defined by Strasser (1913) as the static equilibrium adopted by the upper vertebral body when it is *uninfluenced by external forces or muscular forces He determined* the position of the upper body in relation to the sub adjacent one in terms of *the three angles between the mid lines of the bodies projected in the*

narrowing somewhat towards the back In front the cranial facets enclose the caudal, thereby preventing ventral translation (horizontal displacement instability) of the upper vertebra in each pair (McNab 1950 Lewin, 1964) Otherwise, the joints are designed to permit a relatively considerable degree of rotation around the sagittal and frontal and vertical axes (Guntz 1934 Lewin 1964 1965) Like the intervertebral discs, the intervertebral joints are frequently the site of degenerative processes which is one of the reasons why their load bearing function has been discussed (Guntz 1934 Shore 1935 Severin 1943, Gianturco 1944 Ingelmark 1956 Kelly 1958 Lewin, 1964) In general it has been considered that the intervertebral joints serve as guides for the motion segment (Fick 1904 Keyes & Compere, 1932 Armstrong 1958 Nachemson 1963)

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Roentgenologic studies of motion in vivo

The normal movement of the spine in vivo has been studied roentgenolo gically by a large number of authors (Calve & Lelievre 1913 Junghanns 1931 Backe 1931 Dittmar, 1930—31 a, 1931 b, Elward, 1939 Alvik 1949 Tanz 1953 Leger 1956 Allbrock 1957 Schalimtzek, 1958 and others, see Table 2) A reliable assessment calls for extremely refined techniques Subluxation between lumbar vertebral bod es with neural arches intact (pseudospondylolisthesis, retro- and anteposition) have been demonstrated by e g Junghanns (1931), Johnson (1934) Smith (1934), Severin (1943), Knutsson (1944) Melamed & Ansfield (1947) and Hagel stam (1949) and horizontal translation (instability) by Knutsson (1944) Gianturco (1944), Fletcher (1947) and Schalimtzek (1958) Knutsson (1944) considers that instability is an early sign of disc degeneration Willis (1935) denies the occurrence of backward displacement which he considers to be an optical illusion In X ray examinations during movement in the sagittal plane Hagelstam found up to 2 mm horizontal translation in normal cases instability was demonstrated in case of lumbago sciatica but seldom exceeding 3 mm Examining movement in the sagittal and frontal planes in a single case Dittmar (1930) showed that sagittal and frontal rotation in the motion segment occur around different momentary axes His technique for assessing the roentgenograms is the same in prin ciple as that previously used by Virchow for autopsy specimens Dittmar s calculations however are based on the assumption that the axis of motion according to Fick passes through the centre of the nucleus (located in the posterior third of the disc according to Schmorl 1928) Radberg (1954), in conjunction with discography found that instability displayed before the injection (0 5 cc) disappeared afterwards but could be demon strated again 24 hours later During discography Roaf (1960) found that the position of the nucleus in the disc is not changed by eccentric loading of the specimen Muller (1933) in an X ray study of malrotation in scoliotic spines found that there is an apparent lateral displacement due to the (longer) frontal diameter of one vertebral body being projected

Table 2 *Lumbar motion according to Backe Dittmar and Leger*

	Bending forward			Bending backward			Bending to the side		
Level	B	D	L	B	D	L	B	D	L
L1 L2	2 0	3 0	6 5	6 6	5 5	9 5	3 5	3 25	8 0
L2 L3	3 0	8 3	10 5	8 0	4 0	7 5	4 0	2 75	9 0
L3 L4	3 0	8 3	12 5	9 0	5 5	5 0	5 4	5 75	9.5
L4 L5	3 7	14 3	17 0	10 2	3 5	4 0	4 7	4 75	7 0
L5 S1	2 2	—	12 0	16 4	—	9 5	3 4	—	1 5

sagittal, the frontal and the horizontal planes Virchow (1911, 1928) studied the segmental mobility on a ligamentous spine as follows with the specimen s caudal vertebra held in the horizontal position plaster casts were made of the specimen in the mid position as well as after manual flexion and extension The specimen was then divided in the sagittal plane and macerated, after which the section surfaces were painted white and marked with a sagittal line. The two halves of the specimen could now be placed separately in the plaster casts and moved between the three positions while measuring the change in angle Virchow allows that the method is laborious for which reason he only examined one specimen only a part of the spine and only in the sagittal plane Andersson & Ekström (1940—41) measured the range of movement for individual lumbar segments in the sagittal and frontal planes, using three specimens and varying loads The range of movement was transferred onto a scale by means of a small mirror fitted ventrally and laterally respectively in the periphery of the vertebral body These authors point out that previous results were somewhat arbitrary because the movement was obtained manually with a variation in the strength of the examiner s arm so that the specimen s elastic limit was either not reached or exceeded It proved difficult to achieve rotation in a well defined plane The total movement (—5° to —12°) was partly dependent upon the elasticity of the vertebral bodies Rotation was found to occur around varying momentary axes, the positions of which were not determined

Fick (1904) compared the mobility of the spine with the deformation of an elastic rod the flexibility of which in all directions is directly proportional to the square of the height and inversely proportional to the square of the area of cross section or the fourth power of the diameter Lucas & Bresler (1961) determined the theoretical critical load (P_{cr}) for a segmental column composed of alternating rigid and elastic elements and found good agreement with the empirical values for three human ligamentous spines. P_{cr} = 1 95—2 62 kg for the entire spine fixed at the sacrum only with the upper vertebral body supported, this value is increased about tenfold [1] They also calculated rotation/moment ratios for various levels of the spine. Evans & Lissner (1959 1965) determined the energy absorbtion when specimens were loaded vertically and transversally The highest value was found for vertical loading, with an average of 300 inch pounds (3 4 kgm) Ruff (1950) reported a figure of 4 5 kgm for specimens comprising six vertebrae and demonstrated that the moment of inertia is greater for flexion than for lateral bending

[1] The critical load is the vertical load that causes stability failure or buckling of the rod (the spine)

1962 Ikata 1966) but the intrathoracic and intra abdominal pressure measured directly with a manometer, is greatly elevated (Davis 1956 1959 a, b, Bartelink, 1957 Morris Lukas & Bresler, 1961, Eie & Wehn 1962) and this is calculated to relieve the load on the lumbar discs by 30—40 per cent The aorta, too, has been held to play a considerable role in stabilizing and relieving the spine in vivo (Schantz, 1931) Using chronocyclophotography, Davis et al (1965) demonstrated that lumbar movements usually consisted initially of slight flexion, being followed by continuous lumbar extension When lifting with bent knees the delay in onset of continuous lumbar extension was proportional to the weight of the load"

The lumbar intradiscal pressure has been measured in various postures in vivo (Nachemson 1965) Bending forwards from the upright posture (body weight 70 kg) the total load on the disc of L 3 was calculated to 150 kg and was somewhat greater than this for the sitting posture bending forwards When the subjetct held 10 kg in each hand the load on the disc was increased by 70 kg

Previous studies of physical properties of vertebrae and discs

Bone tissue and vertebral bodies

The reaction of bone to mechanical forces has been the subject of repeated study (for reviews see Evans, 1957 and Knese 1958) Bone may be regarded as a heterogenous or anisotropic material composed of collagenous fibrils and apatite crystals varying in its porosity and moisture content (Dempster & Liddicoat 1952) Bone has been described as a multiphase system comparable with concrete or fiberglass (Knese 1958 Currey, 1964 Mack 1964) Its structure is determined by the arrangement of the collagenous fibrils the basic principle being the spiral The individual fibrils lie in concentric layers those in contiguous laminae lying at an obtuse angle to one another Knese asserts that the collagenous fibrils in bone are prestressed

The physical properties of cortical bone have been investigated with reference to elasticity viscosity and plasticity by Sedlin (1965) and by Sedlin & Hirsch (1966) These properties have been described by Sedlin in a rheologic model for cortical bone

In loading tests on a cube of spongy bone from an adult lumbar vertebra, Rauber (1876) reported a breaking strength of 84 kg/cm In loading tests on whole bodies from lumbar vertebrae, Messerer (1880) found that the breaking strength varied between 22 and 78 kg/cm The first satisfactory report of compression tests on a sizable material of vertebral

bodies (52 vertebrae from 50 individuals) was published by Lange (1902) Each specimen consisted of three vertebral bodies (with the vertebral arch removed) and the intermediate intervertebral discs The body at each end had its outer half sawn off horizontally and the specimen was loaded between two mutually independent metal plates, using a 250 kg lead weight which was lowered onto the loading plate with a double-armed lever Two markers 13—14 mm apart were applied ventrally in the sagittal plane of the middle vertebral body By placing an extenso meter against the two pins the deformation resulting from increments to the load could be read off from a scale between the long arms of the extensometer Lange pointed out that his method gives the deformation between fixed points in the object measured and he rejected all methods that require the use of external reference points (e g a cathetometer, mirror devices dial indicator between the loading plates) After the test, the vertebral body s area of cross section was traced and determined by weighing The breaking strength varied between 15 and 56 kg/cm² and the elastic limit between 5 and 30 kg/cm² The modulus of elasticity was calculated to approx 12 000 It seems, that Lange was unable to avoid buckling of the specimens since the distance between the measuring points sometimes increased

Gocke (1926 1931) compressed lumbar vertebrae from autopsy specimens in an Amsler materials testing machine and compiled stress strain dia grams Breaking strength was said to be 57—70 kg/cm and the compression at the breaking point 15 5 per cent The diagram was markedly S shaped with a large initial deformation, suggesting adaptation at the loading surfaces (since the deformation was measured between the jaws of the loading apparatus) Fully comparable loading tests with similar results have been undertaken by Perey (1957) Decoulx & Rieunau (1958) and Eie (1966) Ruff (1950) determined the ultimate strength of specimens comprising three vertebrae and the intermediate discs Because the specimens tended to jack knife, the surfaces of the outer vertebrae were sawn obliquely so that only the ventral part of the vertebrae received the primary load

In loading tests on vertebrae with intermediate discs, the weakest part of the system has proved to be the end plate (Friberg 1941 Perey 1957 Brown Hansen & Yorra, 1957 Decoulx & Rieunau, 1958 Hardy Lissner, Webster & Gurdjian 1958)

In order to elucidate the aetiology of spondylolisthesis Turner & Markellow (1930) made unsuccessful attempts on 20 autopsy subjects to produce isolated fracture of the laminae by direct blows to the lumbar spine or by forced extension and flexion Rove & Roche (1953) repeated the

attempt in vain on 50 stillborn babies, whereas Hitchcock (1940) required little force to produce bilateral or unilateral laminar fractures by a com bination of flexion lateral flexion and torsion on specimens from 8 months foetuses and babies up to 10 months

Arima (1959) loaded a two dimensional model spine of photo elastic material and showed that maximal stress was concentrated in the region corresponding to the isthmus

Loading tests on individual processes of the vertebral arch have been made by Tylman & Ramotowsky (1961), Harrington (1962) and Waugh (1966) in order to find suitable attachments for devices to correct scoliosis The spinous and transverse processes could be loaded with 15 kg at the most while the pedicles could take more than 100 kg without fracturing

Loading tests on discs

Loading tests on discs have been undertaken with all or part of the adjacent vertebrae retained as a support The vertical compression has been measured between the jaws of the loading apparatus the vertebrae being regarded — for the loads in question — as solid, non compressible parts of the specimen (Gocke 1932 Virgin 1951 Ingelmark & Ekholm 1952 Hirsch & Nachemson 1954 Brown Hansen & Yorra, 1957 Virgin, 1958 Eie 1966) The bulge of the annulus fibrosus during vertical loading has been measured by Hirsch & Nachemson (1954) and by Brown Hansen & Yorra (1957) who report that both compression and bulging are somewhat greater in degenerated than in healthy discs Gocke (1932) found that in young individuals with a high water content in the nucleus the disc displayed considerable elastic deformation on loading In adults the elasticity was complete at least for loads under 70 kg Damage inflicted upon the annulus fibrosus and end plates did not affect the elastic function of the disc Virgin (1951) repeated this test and verified Gocke s results emphasising that the stress strain diagram indicates a viscous elasticity Complete recovery is modified by the duration of the force The inter vertebral disc reaches its greatest state of efficiency in adult life — that is when the nucleus pulposus has disappeared as an entity The function of the disc appears not to depend upon the presence of the nucleus rather does the presence of the nucleus indicate immaturity of the disc Hirsch (1951) used an elastometer to record the tension in the annulus fibrosus during vertical loading The results for degenerated discs varied greatly and it was concluded that the structural changes in the interverte-bral disc altered the conditions in the motion segment, permitting patho logical movements

Nachemson (1960) developed a method for the direct measurement of

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laminae, movement was prevented and the intervertebral joints were partially destroyed With fusion of the intervertebral joint on one side, marked changes were found on the unoperated side as well

According to Haas (1940) growing dogs display a tendency to lordosis after fusion whereas injury to the epiphyseal plates results in kyphosis Dorsal fusion was performed together with curretage of the epiphyseal plates and vertebral bodies in 10 dogs and no deformity was found post operatively He concluded that the fusion had prevented kyphosis In a subsequent experiment on 6 dogs Haas (1946) resected as much of the annulus as possible transperitoneally and scraped the end plates with a curette The five dogs sacrificed after 122—146 days all had bony union and no movement could be found between the vertebral bodies although there was a slight play in the intervertebral joints

Kurtz & Horwitz (1936) tried out Hadras method with metal loops round the spinous processes They reported good primary fixation in 8 dogs but this did not last in any of the animals owing to resorbtion of bone around the loops

Using autopsy specimens from 6 individuals aged 18—68 years Albanese (1922) prepared 10 specimens consisting of three vertebrae and the intermediate discs on these he imitated osteosynthesis by placing metal rods paraspinally and fixing them together with screws Having resected the middle vertebral body, he loaded the specimen from a lever At a load of 60—78 kg one of the specimens fractured through the pedicles and the other through the apex of the spinous process

Azema (1932) performed loading tests on two specimens comprising L 2 to the sacrum from men in their forties The sacrum was held in a screw *vise and subjected to dynamic force along its longitudinal axis* the specimen buckled but there was no sign of vertebral displacement The isthmus was then severed on both sides whereupon the same force produced a 5 mm ventral displacement above the defect After this the lower three vertebrae were fixed to the sacrum with two metal plates The same flexion and displacement was produced with a static load of 30 kg and the author concluded that Albee s method is insufficient in spondylolisthesis The other specimen had metal plates attached to it between the transverse process of L 3 and the sacrum Although flexion and displacement was produced after severence of the isthmus it was less pronounced than in the preceding experiment The osteosynthesis was *considered to correspond* to Lance & Aurousseau s *technique* which was preferred to that of Albee

The fixation potential of metal rods has been investigated by Witt et al (1959) for vertical loading of specimens consisting of the pelvis sacrum,

lumbar spine and lower thoracic spine Long metal rods or Kuntscher nails were fixed with cerclage or screwed to the spinous processes, transverse processes or vertebral bodies or else they were introduced intraosseously down the vertebral bodies It was considered that reliable fixation of a section of the spine could be achieved only with two strong steel rods (Lane's plates) screwed paravertebrally and involving several segments This also produced a remarkable straightening of the unfixed parts of the spine The method cannot be applied in practice in vivo Paraspinal fixation gave acceptable stabilisation except against torque Harris & Wiley (1963) imitated bony union in autopsy specimens by embedding the vertebral arches in methyl acrylate A combination of flexion and torsion produced spondylolisthesis though usually as a secondary phenomenom in larger injuries They considered that the weakest part of the fusion was the isthmus and that spondylolisthesis probably represents a stress fracture Six specimens were examined but no details of the method were reported

Arima (1958) studied the distribution of stress in photo-elastic models of a vertebral segments, with three different types of fusions, with the segment in the mid position and in various degrees of ventral flexion On the assumption that the isthmus is the weakest region of the fusion *fixation between pedicles and intervertebral joints was recommended* for fusion in the mid position or slight kyphosis. As kyphosis increases a ventral graft places greater stress on the isthmus than before the operation In pronounced kyphosis (gibbus) no type of fusion is effective

In experiments on plastic models of the spine, Pennal et al (1964) demonstrated that screws through the articular processes do not give reliable fixation of the motion segment. Little violence was needed to produce a fracture through the facets. Stability was improved, however by a combination of paraspinal metal rods while a contoured plate against the lamina proved four times as efficient as screws alone. These authors report similar results with experiments on autopsy specimens.

Unander Scharin (1950) investigated the effect of dorsal fusion as a means of relieving the tension on the disc. Nine autopsy specimens comprising the lumbar spine and sacrum were subjected to osteosynthesis with metal rods fixed through the spinal processes of L 4, L 5 and S 1 The specimens were loaded vertically before and after the osteosynthesis with 12 5 25 and 37 5 kg During loading a pelotte was held against *the annulus fibrosus with a force of 1 2 and 3 kg* respectively The pelotte's penetration of the annulus increased within the fusion and decreased in the other free discs this was taken as a sign of load relieving effect within the fusion and increased stress on the free discs.

III Materials and methods

Preparatory investigations were first made into the possibilities of imitating fusion in a satisfactory manner on fresh spinal specimens Once this had been done, loading tests were conducted in an *Amsler materials* testing machine in conjunction with measurements of intradiscal pressure according to Nachemson It was soon found that the results varied greatly according to the type of fusion employed and the way in which the load was applied (Rolander 1961, 1963) Specimens consisting of more than one segment could not be prevented from buckling which meant that the distribution of the applied load could not be defined The deformation of the disc as well as of the vertebrae was such that it could not be followed with measuring dials attached to the loading device

Experience from preliminary investigations on some thirty spinal specimens has resulted in the assembly of the apparatus described below and the definitive design of the method

Preparation of the specimens

Preparation of the specimens

During routine autopsies at the department of pathology Sahlgrenska Sjukhuset *specimens* consisting of the entire *lumbar spine* were taken if possible together with the upper part of the sacrum The specimens were hermetically sealed in plastic bags and stored in a deep freeze at —29° C Prior to testing they were left to thaw at room temperature *removed from the plastic bag and dissected free from fat and muscle taking care to preserve the ligaments* Each *lumbar spine was divided* as a rule into two specimens each consisting of two vertebrae with the intermediate disc and ligaments Specimens incorporating two or more discs were sometimes used for special purposes The outer end plates of the vertebrae were scraped clean of disc tissue after which the bottom *half of the caudad body was embedded with plastic in a metal form* designed for use with the loading apparatus described below In order to avoid play as a result of shrinkage the embedding material was permit-

ted to spread over the edges of the metal form and was also transfixed with steel nails running diagonally through the sides of the form. Polyester was used for embedding the specimen with kaolin as a filler and reinforced with fiberglass. The cranial surface of the upper vertebral body was also covered with plastic to make a completely flat horizontal loading surface (checked with a spirit level). No effort was made to line up the upper or lower plane of the disc horizontally. When the casting started to harden the specimen was once more sealed into a plastic bag and stored at −6°C in order to reduce the temperature rise during the hardening process. A piece of moist blotting paper was placed next to the specimen though not touching it so as to maintain a high relative humidity. The plastic casting having cooled, a fixture was used — with the specimen still wrapped in foil — to drive four centre nails into each vertebra: one in the spinous process, one in the ventral periphery of the body and one in the lateral periphery on either side of the body. The nails were placed so that each quartet lay in a horizontal plane, with a distance of 20—25 mm between the corresponding nails in the two vertebrae (depending on the height of the disc). The ventral and dorsal nails represent points in the sagittal plane of symmetry, while the lateral nails lie in a frontal plane at right angles to the sagittal plane (see Figs. 1, 15 and 16).

Various methods were tried to imitate healed fusion. Metal plates and screws proved inadequate since the screws created structural faults and the specimen could not be loaded up to physiological levels. The best results have been achieved with plastics (Mandarino 1960, Rietz, 1964). All plastics, however, are sensitive to fat during hardening and will not adhere properly to fresh bone. Nevertheless good fixation can be obtained if, during hardening, the plastic material shrinks somewhat round the embedded parts of the bone. Polyurethane expands during hardening and consequently is unsuitable. Although epoxy resin has many advantages, hardening either takes an excessive time or is highly exothermic. Polyester (Soredur H40), which has an elastic modulus for bending of 39 000 kg/cm², gives suitable shrinkage. The hardening time is easily controlled but with the quantities required for experimental fusion (50—150 cm³) the maximum temperature is about 90° C. By taking a number of special precautions, however, hardening could be achieved without exceeding physiological temperatures measured immediately ventral of the fusion. Thus, the casting was made in a plasteeine mold which screened the rest of the specimen, kaolin was used as a filler, the casting was applied in layers and the specimen was stored at a low temperature during the exothermic period of hardening (Fig. 2).



Fig 1 (a, b)
Lateral and antero-posterior X ray views of a specimen (nr 14 L2—L3) in the compression apparatus



Fig 2 (a, b)
Specimen nr 14 L2—L3 seen from the posterior superior aspect in preparation fo casting The anterior elements of the specimen are isolated by plastecine and the remainder of the casting mold is made up of a piece of X ray film



Fig 3 *The complete casting of a fusion type 3 (c f Fig 4)*

Experimental devices

The investigations were made with the following apparatus

1 *Compression apparatus* (Fig 7)

The compression apparatus has a cast iron base, four steel corner pillars and on top a steel plate 10 mm thick A stage in the base can be adjusted with micrometer screws in two directions at right angles to one another in the horizontal plane and can also be rotated about a vertical axis In addition the stage can be rotated on a horizontal axis so that it slopes to a variable degree to the horizontal plane The specimen in the metal form described above is securely bolted to the stage In the centre of the top plate of the apparatus there is a piston, the connecting rod of which runs in a stable ball bushing The piston is driven by compressed air from a gas tube the rate of loading being controlled manually with standard valves

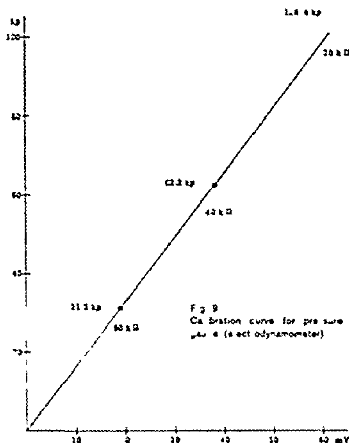
The load is applied from the piston via a measuring head (Fig 8) with two electrodynamometers (Bofors KRK-1) each with a range of 0—100 kp The loaders are fastened with turn buckles to a plate of hardened steel 10 mm thick down the middle of which there is an edge designed to impart a linear vertical load The angle of this edge to the horizontal plane is adjustable with a screw The loading unit is rotatable about the piston its movements being indicated on a graduated dial Between the top of the specimen and the loading edge there is a steel face-plate and on this a trolley resting on four ball races. With this arrangement the specimen's freedom of movement with respect to rotation and horizontal translation is limited to a plane perpendicular and at right angles to the loading edge Consequently the loading force exerted on the specimen can be clearly defined in terms of size position and direction Each load can be reproduced even though the specimen has been removed from the apparatus in the interval

2 *Elec rodynam om e ers*

The principle of the dy ... er is based upo ... ormation of a ring which is loaded at ... opp ... This induces elongation at the p ... this is con ... its electrical equivalent by means ... ges. The for ... easured is trans mitted via two end ... have so ... play and are con ... tly almost ... m ... mom ... ele ... eters ar ... calibr ... h ... on resis

Fig 7
Complete testing apparatus with the amplifier for the disc pressure transducer on the left loading device in the center and carrier frequency system monitor and recorder on the right

Fig 8
The specimen fixed beneath the loading head with the pressure transducer visible in the background on the left and the applied displacement gauges and extensometers seen surrounding the specimen



F g 9
Ca bration curve for pre sure gau e (e ect odynamometer)

1 , 12
Ex ensome e



Fig 13
D s, acement gauge



S e an v e g ed ap, a a n for mecanical calibration — b m e ome e

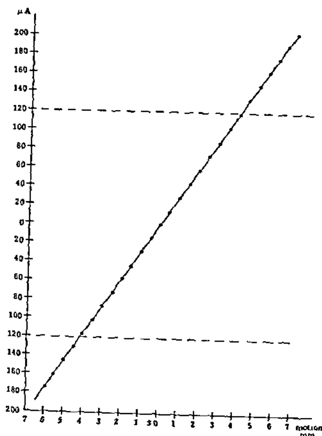


Fig 11
Calibration curve for differential transformer r 1

3 *Displacement gauges* (Fig 10)

For the measurement of displacements a gauge of the induction type was constructed (Svensk elektronikkonsult Goteborg) known as a differential transformer The transformer is wound onto a teflon bobbin in which there is a movable soft iron core with a brass shaft and a measuring tip of anti magnetic stainless steel The differential transformer is 40 mm long with an external diameter of 8 mm Including the leads it weighed 10 g The millimeter thread of the bobbin can be used for simple mechanical calibration since one revolution of the differential transformer in the housing corresponds to a 1 mm displacement of the core The gauge is however wired as a balanced bridge and by virtue of its electrical design it is simpler to calibrate with a fixed precision resistances The linear deviation for the range of measurements in question is less than 1 per cent (see Fig 11) The gauges have been calibrated

regularly against a micrometer without it being found necessary to undertake any correction of the precision resistance. Three gauges of this type have been used for registering the movements of the specimen in the horizontal plane (translation).

4. *Extensometers*

The design and mechanical calibration of the extensometers produced for measuring displacement in the vertical plane are illustrated in Fig. 12. The extensometer is shaped like a scissors, with pointed ends to the "blades" and a differential transformer (see above) mounted at the ends of the "handles". It is of brass 15 cm long, with a total weight of 50 g. All its joints are fitted with ball bearings. The position of the central axis makes it possible to suspend the extensometer in rubber bands against the specimen with a satisfactory balance and minimal measuring pressure. The extensometer can be zeroed in keeping with the initial distance between the measuring tips. Its range of linear measurement is the same as for the differential transformer when used by itself. Five extensometers of this type have been used for the measurements: three to measure the vertical deformation of the disc, one to show the movement between the spinous processes and one to measure any deformations in the periphery of the upper vertebral body.

Recording devices

The two dynamometers and eight motion gauges were connected to a specially designed servodriven switch monitor (AB Svenska Philips and Svensk Elektronikkonsult, Goteborg). A carrier frequency system (Philips BF 2) is connected manually or automatically at a stage rate of 0.3—1 gauge/sec, each channel having a special unit for balancing and zeroing, an amplifier and a calibration resistance. The signals are transmitted to a one-channel potentiometer recorder (Philips PR 2210 A 21). The monitor also connects two reference channels and two unutilized steps, so that a single cycle (loading interval) lasts 14—46 sec. The recording paper is 250 mm wide and the error of the writer is 0.25 per cent of full deflexion. A paper speed of 75 mm/min was used throughout. As a rule, the displacement gauges were calibrated so that full deflexion on the writer corresponded to ± 5 mm, the figure for the dynamometers being ± 100 kp. The reading error is ± 5/1000 mm and ± 0.1 kp respectively.

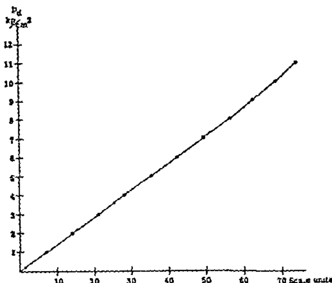


Fig 13
Spec nr 19 L3–L4
Calibration curve for intradiscal pressure

Intradiscal pressure gauge

Intradiscal pressure was measured by the method described by Nachemson (1960) The discs is perforated with a needle diameter 1 1 mm closed at the end and fitted with a pressure-sensitive polyethylene membrane The deformation of this membrane is transmitted via a closed water filled system to a mechano electrical transducer of the Statham type (modified by Svema Elema, Sweden) The movement of the membrane is transmitted by the column of water to the copper membrane of the pressure transducer and converted via strain gauges into electrical equivalents and read off directly from the measuring bridge The pressure transducer is calibrated against known pressures in a pressure chamber before and after each experiment The error of the method has been calculated by Nachemson to approximately 3 per cent (Fig 13)

X ray unit

The unit used was a portable machine with a 2 mm focus The focus film distance was 250 cm and the film target distance 6 cm Pictures were taken of the entire lumbar spine before dissection and also of each specimen in the loading apparatus without and with fusion in the sagittal and frontal planes and at the end of the experiment, a picture in the specimen s longitudinal axis (Figs 1 and 15) The enlargement is less than

3 per cent. The X ray pictures were used for measuring the initial angle of the disc (α) as formed by the tangents to the projections adjoining surfaces of the vertebral bodies (Fig. 16). This angle has been given a positive sign in flexion and a negative in extension. A linear measure was provided in the X rays by the projection of a bolt with a millimeter thread which gave a scale divided into half millimeters. The linear dimensions of the vertebrae were measured from the frontal and sagittal projections with a pair of dividers (see Fig. 16 p. 44).

Planimeter

After the experiments the disc was sectioned horizontally and placed against a sheet of glass. The outline of the horizontal section was then copied onto tracing paper (Fig. 15) for calculation of its area with an Amsler planimeter to an accuracy of 1/10th cm. The planimeter was checked by measuring a known surface of the same order of magnitude before and after each measurement of a disc. The planimeter was also used to calculate the mean height of the disc.

Description of the loading test

The specimen embedded in its metal form is firmly bolted to the stage of the loading apparatus and encircled with a "cage" of brass rods. The clamps for the horizontal displacement gauges are then adjusted so that measuring rods of suitable length can be fitted horizontally in the specimen's sagittal plane and held against the centre nails with rubber bands between the cage and the shaft of the iron cores. Two gauges are lined up with the ventral measuring points on the bodies of the upper and the lower vertebra respectively, a third being lined up with the spinous process of the upper body. The extensometers for the measurement of vertical displacement are attached to the cage with rubber bands in a similar manner so that their measuring points are held against the pairs of centre nails on the two vertebrae. Thus one extensometer rests against the ventral aspects of the two vertebrae, one against each of their lateral aspects and one against the spinous processes. In addition one extensometer is placed with both its measuring points against the upper vertebral body. In each case the caudal centre nail serves as a reference point for the vertical displacement between the points of the extensometer. The extensometers are balanced by adjusting a lead weight suspended from the upper handle and the rubber bands are tensed just sufficiently to hold the measuring points against the centre nails. The loading stage has a very slight play which proved difficult to eliminate. It is, however, recorded by the motion gauge against the lower

vertebral body and the readings from the motion gauges against the upper vertebra can be corrected accordingly It follows that all measurements are derived from points on the specimen and no external references are required

The loading stage — with the specimen and motion gauges — is now adjusted so that the plane of the loading edge coincides with the frontal plane through the four lateral centre nails in the specimen The steel plate and trolley are placed on top of the specimen a trial load is applied and the angle of the loading edge to the horizontal plane is adjusted to obtain even compression in the frontal plane.

The disc is perforated anterolaterally or posterolaterally the pressure-sensitive needle is inserted so that its pressure receptor lies in the centre of the disc and the pressure transducer is clamped to its stand

The motion gauges and dynamometers are zeroed and calibrated With the first dynamometer connected to the writer (channel 9 Fig 14) the air valve of the compression apparatus is opened and the load is read

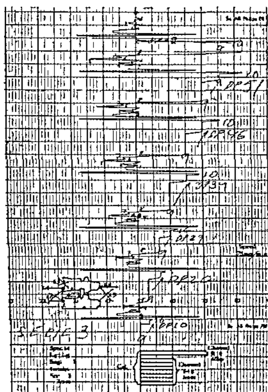


Fig 14 *Reproduction of a recording from a single loading sequence (series)*

off. Once the desired load has been obtained the air valve is closed and the switching unit is set for automatic registration of all the gauges. When the writer registers channel 9 a second time the switching unit is turned off. The load is now increased one interval and the new readings of the gauges are recorded in the same manner as before. The intradiscal pressure at each load is also read off and recorded. The load is increased by stages to a maximum of 200 kp. The vertical gauge on the body of the upper vertebra is checked to ensure that there is no displacement of the body. Should any displacement occur the specimen is unloaded. After unloading recordings are made of residual displacements.

Once the residual displacement at the end of the first loading sequence has been recorded the specimen and loading stage are shifted in the sagittal plane so that the same sequence of measurements can be repeated with ventrally (+) or dorsally (—) eccentric loads the change in position as a rule being 5 mm at the time. A record is also generally kept of the degree of eccentricity (in millimeters from the initial position) at which the applied load results in compression of the specimen without altering the angle of the disc in the sagittal or frontal plane ("balanced position").

After the loading sequences in the sagittal plane have been completed the specimen is turned 90° prior to studying rotation in the frontal plane (lateral flexion). For this the vertical motion gauges are placed against the same measuring points as previously whereas the horizontal gauges now coincide with the frontal plane, one against the lower and one against the upper vertebral body's right hand measuring point and one against the upper vertebral body's left hand measuring point. The measuring sequences described above are now repeated first with the loading edge in the sagittal symmetry plane then eccentrically to the right ( ) and left (—).

Special measures such as division of ligaments fixation of intervertebral joints with screws or resection of such joints, can be undertaken without removing the specimen from the loading apparatus and further loading sequences can be performed directly. The specimen has to be removed, on the other hand for the casting of fusion. The plastic cast is left to harden for at least two hours before the specimen is reinserted in the loading apparatus after which the loading sequences can be continued under the same conditions as before.

Upon the completion of measurements on fused specimens, the disc is excised (as a rule this can be done without detaching the motion gauges) and the specimen is then loaded until it fractures.

Before being excised, the disc is generally injected with chromopaque The area of the resected disc s horizontal cross section is measured with the planimeter as described above The pathological condition of the disc is assessed by macroscopic inspection

After the vertebral specimen has been examined roentgenographically, it is sawn through for investigation of the fractures and to check that the fusion cast has not loosened from the bone or base plate

Terms and definitions

1 The *measuring points* of each vertebra have been numbered as shown in Fig 15

2 *The distance between points 1 and 5 (L) has been measured on sagittal* X rays with an accuracy of 0 5 mm (allowing for roentgenographic en largement) and rounded off to the nearest millimeter

3 The *initial height* of the disc (h_1 h_2 h_3 h_4) has been measured on X rays as the distance between the edges of the vertebrae on the vertical line connecting each measuring point and its corresponding reference point. The *mean height* of the disc has been calculated by measuring the surface of the disc in the lateral X ray with a planimeter and dividing the result by the sagittal diameter (d)

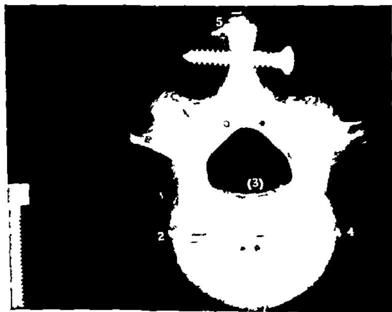


Fig 15
Radiographic view of specimen nr 17 L1—L2 taken from above demonstrating placement of measuring points 1—5 in the vertebra

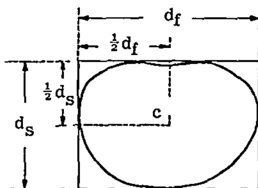


Fig 17
Direct tracing of the sectioned disc (Spec nr 17 L1—L2) with dimensions applied

sagittal rotation) and a negative for extension (negative sagittal rotation)
9 The change of angle in the frontal plane (β) has been given a positive sign for lateral flexion to the right (positive frontal rotation) and a negative to left (negative frontal rotation)
10 Rotation around the longitudinal axis torque- (γ) is counted positive in the clockwise direction
11 The *vertical displacement* (δ_v) of a measuring point is the recorded change in the distance between the measuring arms of the extensometer and carries the number of the measuring point (δ_{1v} δ_{v} δ_{4} δ_{5}) the sign being negative for a decrease and positive for an increase of this distance
12 *The horizontal displacement* of a measuring point is designated in a similar way (δ_{1h}, δ_{h} δ_{4h} δ_{h}) with a positive sign for displacement ventrally and to the right and a negative for displacement dorsally and to the left
13 S is a correction factor for measuring points 2 and 4 (see Fig 16)
14 *The unit displacement* (ε) is the quotient of the vertical deflection and the initial height for a loading interval and is designated according to the measuring point (ε_1 ε ε_3 ε_4)
15 The lumbar spines used in this study have been numbered conse cutively each specimen being designated by this number and the vertebrae involved e g no 13 L 3 — 4 The discs are identified by the number of their cephalad vertebra
16 Loading of the specimen has been done in stages from zero to a maximum unloading has been done straight to zero The displacements arising at each loading stage have been recorded for the individual measuring points The loading sequences have been numbered consecutively

Nr 14
L4–L5

Scale: Each mm represents 0.5 mm displacement and d.] of the measuring point and ... mm distance along the specimen.

Fig 19 a.
Motion in sagittal plane represented by horizontal and vertical displacement of points 1, 3 and 5 in a fixed specimen with increasing load applied 20 mm behind the geometric centre.

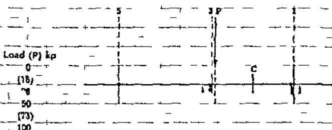


Fig 19 b
load applied centrally (±3 mm)



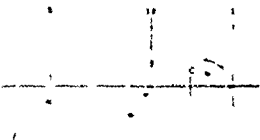
Fig 19 c
load applied 10 mm in front of the geometric centre.

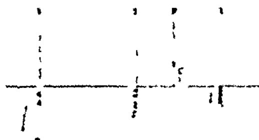


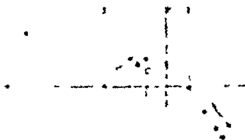
Fig 19 d.
Fixed spec. after excision of the disc, loaded centrally (±3 mm)



Load P kp
0
6
20
36
52
74
93
118
134
145







Scale | Each unit represents .5 m displacement and 1 of the measuring point and 5 mm distance along the specimen. | Nr 13 L1–L2

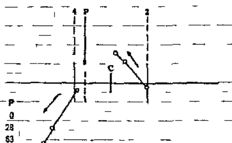


Fig. 20 a.
Motion in the frontal plane (lateral bending) represented by horizontal and vertical displacement of points 2 and 4 in an intact specimen with increasing load applied 14 mm to the left.

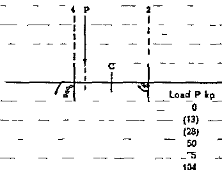


Fig. 21 a
Motion in frontal plane (lateral bending) represented by horizontal and vertical displacement of points 2 and 4 in a fused specimen with increasing load applied 14 mm to the left.

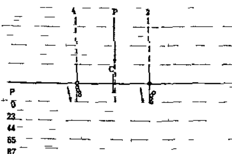


Fig. 20 b
load applied centrally (+1 mm)

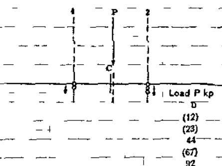


Fig. 21 b
load applied centrally (+1 mm)

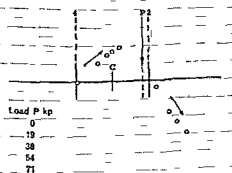


Fig. 20 c
load applied 16 mm to the right.

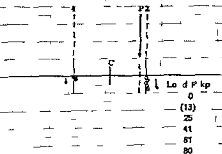
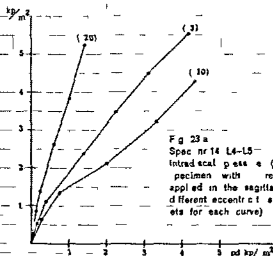
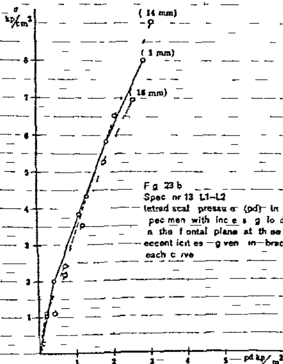


Fig. 21 c
Load applied 16 mm to the right.



F g 23 a
Spec nr 14 L4–L5
Intrad scal p ess e (pd) n a fused pecimen with reasing load (σ) appl ed in the sagittal plane at three d fferent eccentr c t s (g en n brack ets for each curve)



F g 23 b
Spec nr 13 L1–L2
Intrad scal pressu e (pd) in a fused pec men with inc e s g lo d appl ed n the f ontal plane at th ee different eccent icit es g ven in brack ts for each c rve

Thus the initial position of the upper vertebral body is represented by a horizontal ellipse with the short sagittal diameter (d_s) between points 1 and 3 and the long diameter (d_f) between points 2 and 4 During loading this plane rotates in relation to the corresponding horizontal reference plane through the lower vertebral body Its position at each stage of

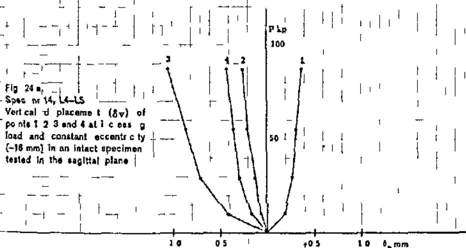


Fig 24 a. Spec nr 14, L4–L5 Vertical displacement (δv) of points 1 2 3 and 4 at increasing load and constant eccentricity (~16 mm) in an intact specimen tested in the sagittal plane

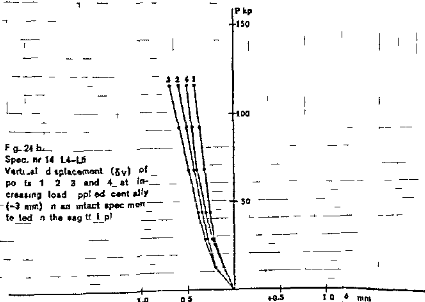


Fig. 24 b. Spec. nr 14 L4–L5 Vertical displacement (δv) of points 1 2 3 and 4 at increasing load applied centrally (~3 mm) in an intact specimen tested in the sagittal plane

The relationship between the change in angle and the displacement on the one hand and the eccentricity at constant load on the other is illustrated in Fig 26 for intact specimen and in Fig 27 for the same specimen after fusion.

Fig. 26 a.
Spec nr 14 L4–L5
Change of angle in the sagittal plane at three constant loads and various eccentricities in an intact specimen.

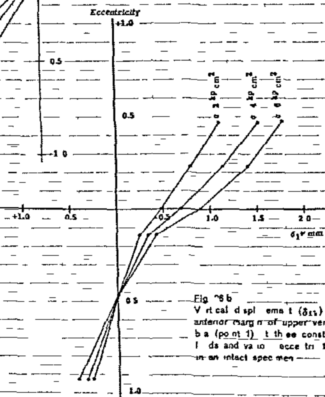


Fig 26 b
Vertical displacement (δ_{11}) of anterior margin of upper vertebra (point 1) at three constant loads and various eccentricities in an intact specimen

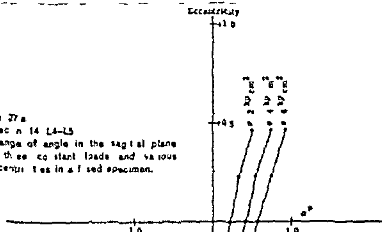


Fig. 27 a
Specimen 14 L4–L5
Change of angle in the sagittal plane at three constant loads and various eccentricities in a fused specimen.

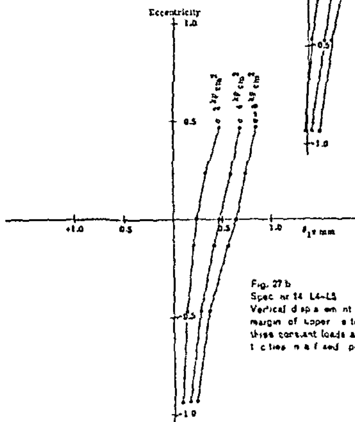
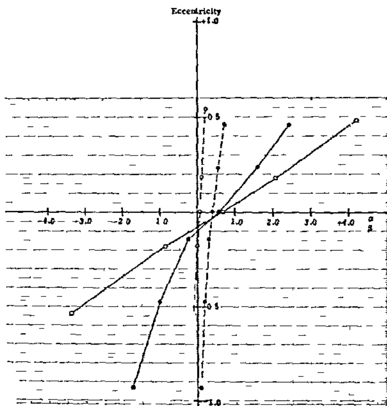


Fig. 27 b
Spec. nr 14 L4–L5
Vertical displacement (δ_{1v}) of anterior margin of upper vertebra (point 1) at three constant loads and various eccentricities in a fused specimen.

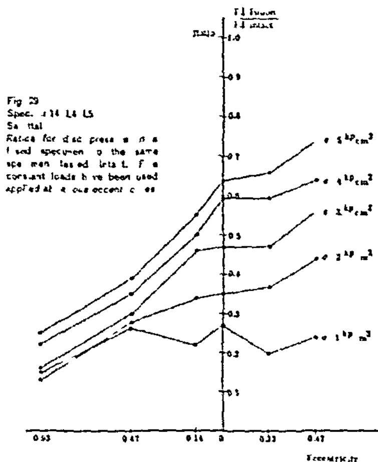


F g 28
Nr 14 L4–L5
Cange of angle n o e spe men w th o tant load (σ=4 kp/cm²) appl d at var o s eccent tr c t s n sag ttal (α) and f ontal (β) plan s both nt ct and after fus on
● = S g ttal
○ = F ontal
—— = I tact
= Fus on

In order to visualize the three dimensional movement of the segment during various loading conditions and after different treatments of the specimen graphs such as those shown in Fig 28 were compiled for a particular load per unit area (4 kp/cm²) with the change in angle (α and β) and the relative displacement at a point in the plane (ε_1 and ε_2) plotted against the degree of eccentricity during loading in the sagittal and frontal planes for an intact specimen and after fusion

Comparisons between intact specimens and specimens with fusion or some other procedure are made on the basis of the ratio between the respective

values at the same load for α, β, δ_k, δ, ε and p_d as shown in Fig 29 in this way one can demonstrate the percentage effect of the fusion on the various properties.



Discussion of the method

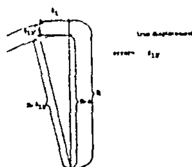
The method described above is in many respects a compromise solution. Although problems which have cropped up during the development work have been mastered to some extent by modifications to the apparatus etc certain difficulties have necessitated a revision of the original aims. Concerning the apparatus, it would have been preferable to make simultaneous recordings of the displacement of several points on the vertebral

body, the vertical and horizontal displacement of the disc towards the vertebral foramen and the protrusion of the disc s periphery The posterior region of the disc was not available for direct measurements with the vertebral arch intact

The simultaneous registration of data via separate channels would have simplified the analysis of the measurements and provided recordings during a continuously increasing load This was not possible for financial reasons With recordings over a single channel there is a danger of errors due to hysteresis On the other hand, repeated recordings at a constant load did not result in significant differences The routine aquired from numerous experiments has meant that variations in the rate of loading are remarkably small (cf Fig 14) and probably irrelevant for the displacements in question, particularly as the method of registering the data allows sufficient time for the specimen to become stabilised in a new state of equilibrium

The intradiscal pressure was recorded at the centre of the disc It was found that during eccentric loading the recorded pressure varied in different parts of the disc Consequently, one would like to use several pressure receptors and record the pressure in different parts of the disc simultaneously besides making simultaneous recordings at several levels in specimens comprising a larger number of segments The disc pressure method requires repeated calibrations against known pressures during the course of the experiment and the data has to be rejected if the calibrations deviate more than 5 per cent (cf p 39) A transducer was modified for the measurement of differential pressure but the attempt had to be abandoned owing to the difficulty of regulating the counter pressure with sufficient precision Trials have also been made with a strain gauge attached directly to a metal membrane at the measuring point so far however such a device has not proved serviceable The method employed in the present study is intended for the measurement of hydrostatic pressure which cannot a priori be considered to be obtained in severely degenerated discs Nevertheless, the pressure has been recorded if it proved reproduceable in repeated series This data is not however intended to represent hydro static pressure equal throughout the nucleus but simply as an expression of the deformation of the nucleus tissue in the centre of the disc

There is an error in measurement inherent in all motion gauges (Fig 30) For rotation of the specimen about a horizontal or vertical axis the new position of the horizontal motion gauge s measuring point lies on the arch of a circle having a radius equal to the length of the measuring arm for the horizontal gauge this is approximately 80 mm Since the vertical



$$(R\ X) + \delta_{1h} = (R - \delta_{1v})$$

$$X = R\left(1 - \sqrt{1 - \frac{\delta_{1v}}{R} \mp \frac{\delta_{1v} - \delta_{1h}}{R}}\right)$$

$$X \approx R\left(1 - 1 + \frac{\delta_{1v}}{R}\right) = \delta_{1v}$$

Fig 30
Meas ng e ror in the e tensomete s

displacement is maximum ± 5 mm, the correction for the horizontal deviation is given by the sine of a very small angle and thus does not affect the recorded value Similarly, for horizontal displacement of the measuring point the vertical motion gauge indicates the point s deviation along the arch of a circle with a radius equal to the distance between the tips of the gauge s legs this distance is 25 mm ± 5 mm Owing to the relatively short radius for the vertical gauge, a large horizontal deviation can result in a large percentage error in the vertical displacement However the horizontal deviation has been small both in absolute and in relative terms (Figs 45 thru 47)

Calculation of change in angle of the segment makes use of the frontal diameter (d_f = 51 ± 7 mm) and the sagittal diameter (d = 39 ±6 mm) and the distance between points 1 and 5 (L 81 ± 13 mm) An error of ± 1 mm in measuring d_s gives an error for the angle β of less than 2 per cent The same error for d gives an error for α of less than 3 per cent (α calculated from L yields less than 1 5 per cent) If, in addition, one allows for a maximum error of ±0 03 mm in measuring the vertical displacements the calculations of β and α incorporate errors of ± 0 04° and ± 0 05° respectively This means that the calculated value of δ_3 contains a relatively large percentage margin of error for small angles (less than 1 degree) and consequently it has not been used for comparisons between specimens.

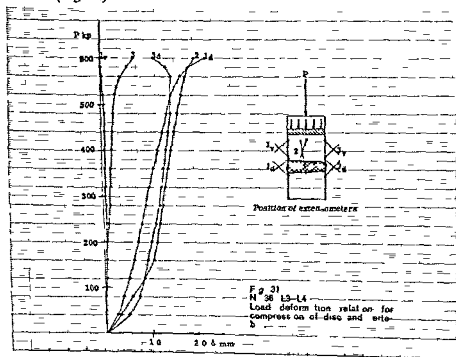
ε is the ratio between two units of length (δ_v/h) for each stage of loading A strictly mathematical calculation requires the use of logarithmic values for addition over several intervals The non logarithmic values have in fact been used but this only affects the fifth place of decimals whereas the results have been taken to three places of decimals only

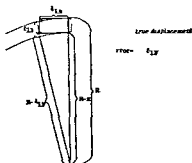
The area of the unloaded disc (A) is included in the calculation of the load per unit area (σ = P/A) which is an expression for the mean load on the surface A On vertical compression of the disc, A increases by up to approximately 5 per cent (Nachemson 1960) This means that

for an increased total load, σ is somewhat larger than the mean load on the disc (calculated from the true area) and less to roughly the corresponding extent, than the mean load on the end plate and the vertebral body

On loading the distribution of forces within the specimen is uneven One obtains a statically indeterminate system for the calculation of these internal forces in a section Such a calculation cannot be made without knowledge of the physical properties and geometry of the specimen Approximate calculations of the distribution of forces have been tried (with arbitrary assumptions concerning the geometry and physical properties) in order to study the order of magnitude of forces active in different parts of the system However, these calculations contained so many suppositions that their value was questionable

As already mentioned, checks were made during the loading tests to ensure that there was no appreciable vertical compression in the vertebral body otherwise the vertical displacement of the measuring points could not be equated with the vertical deformation of the disc between measuring point and reference point In fact, there is unlikely to be any appreciable vertical deformation of the vertebral body judging from compression tests made with heavy loads on specimens in an Amsler materials testing machine and measurements of deformation with the extensometers already described (Fig 31)





$$(R-X) + \delta_{1h} = (R-\delta_{1v})$$

$$X = R\left(1-\sqrt{1-\frac{2\delta_{1v}}{R}+\frac{\delta_{1v}-\delta_{1h}}{R}}\right)$$

$$X \approx R\left(1-1+\frac{\delta_{1v}}{R}\right) = \delta_{1v}$$

Fig 30
Measuring error in the extensometers

displacement is maximum $\pm$ 5 mm, the correction for the horizontal deviation is given by the sine of a very small angle and thus does not affect the recorded value Similarly, for horizontal displacement of the measuring point the vertical motion gauge indicates the point s deviation along the arch of a circle with a radius equal to the distance between the tips of the gauge s legs this distance is 25 mm $\pm$ 5 mm Owing to the relatively short radius for the vertical gauge a large horizontal deviation *can result in a large percentage error in the vertical displacement* However the horizontal deviation has been small both in absolute and in relative terms (Figs 45 thru 47)

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Fig 31 where the end plate fractures at the load at which the deformation curves for disc and vertebral body tend towards one another

Post mortem changes constitute an elusive source of error in all studies on autopsy specimens Since it was not always possible to test the specimens at the time of sampling all specimens were immediately frozen in order to ensure maximum uniformity Freezing is not considered to affect the physical properties of bone (Perey, 1957 Evans, 1957, Sedlin 1965 Sedlin & Hirsch 1966) intervertebral discs (Bartelink 1957, Hardy, Lissner Webster & Gurdjian, 1958, Nachemson 1960) or ligament (Viidik & Lewin, 1965) No change in the extensibility and elasticity of human ligamenta flava was found after unprotected storage in a refrigerator (Åkerblom 1948) The load elongation correlation of rabbit ligaments tested fresh and after storage for 2—96 hours at room temperature was studied and no definite difference was found in tensile strength in spite of histological signs of autolysis, (Viidik, Sandqvist & Magi 1965)

The physical properties of both bone (Rauber, 1876, Evans & Lebow 1952 Smith & Walmsley, 1959 Sedlin, 1965, Sedlin & Hirsch 1966) and ligament (Walker Harris & Benedict, 1964, Viidik, Sundqvist & Magi 1965 Viidik & Lewin 1965 Galante & Hirsch 1966) are sensitive to dehydration and increases in temperature Fresh bone is a poor thermal insulator (Thompson 1958 Sedlin 1965) probably owing to its high moisture content The physical properties of rat tail tendon were not affected by a change from freezing at —35° C to +37° C but irreversible changes occurred above approximately 40° C (Rigby Hirai Spikes & Eyring 1959) The critical temperature for collagen is reported to be 47—48° C (Delaunay et al, 1956 Verzár 1957)

In the present study consideration has been paid to these factors as described on pp 29—30

In several preliminary trials the specimen was stored in a refrigerator for up to one week after testing without and with fusion and then re tested in the reverse order i e. first *with* fusion and then with the fusion removed The results showed no appreciable difference in respect of either deformation in the disc or the intradiscal pressure It was also found that, with the type of loading in question repeated loading series do not affect the physical properties thereby confirming previous investigations on comparable specimens (Gocke 1931 Virgin 1951 Hirsch & Nachemson 1954 Nachemson 1960 Sedlin 1965 Sedlin & Hirsch 1966)

Material

This experimental study was made on 71 samples of human lumbar spines, obtained from 38 autopsy subjects ranging in age from 4—76 years The postmortem examination and specimen sampling

Table 3 *The Study Group*

Subject no	Autopsy no	Age Sex	Body weight	Length	Time in hospital days	Cause of death
1	*II-98*	*44 F*	—	—	3	*Perf ulcer (op)*
2	I 586	6 M	17	—	4	Cardiac failure (op)
3	I 607	4 M	—	—	1	Malignant laryngitis
4	*II-101*	*65 F*	—	—	12	*Pulm embolism*
5	L 100	64 M	—	—	0	Suicide
6	I-717	40 M	—	—	1	Acute myocarditis
7	L-49	34 M	—	—	0	Suicide
8	I-1094	74 M	60	170	0	Cardiac failure
9	I 1194	44 F	59	165	9	Uremia
10	I 1199	54 F	53	160	6	Bronchopneumonia
11	*II-250*	*64 F*	—	—	*31*	*Reticle cell sarcoma*
12	L-84	67 M	—	—	(>13)	Bronchopneumonia (senility)
13	I-1390	53 F	—	—	7	Bronchopneumonia
14	L-86	48 M	—	—	0	Cardiac failure
15	I-1458	61 M	72	—	15	Acute leukemia
16	I-1467	65 M	86	170	1	Myocardial infarction
17	I-1468	70 F	78	160	2	Myocardial infarction
18	*II-272*	*76 F*	—	—	10	Circulatory failure
19	II-276	58 M	—	—	1	Myocardial infarction
20	I 1481	58 M	—	—	1	Myocardial infarction
21	I-1483	61 F	61	160	5	Cerebral contusion
22	I 1511	43 M	70	185	1	Bronchopneumonia
23	I-1513	44 M	59	158	14	Bronchopneumonia
24	II 280	30 M	61	—	14	Inestinal carcinoma
25	I-105	64 M	—	—	1	Uremia
26	II-27	56 M	—	—	6	Pulmonary carcinoma
27	II-29	62 M	—	—	1	Pulmonary carcinoma
28	I 201	52 F	48	—	10	Hepatic failure
29	L-25	32 F	—	—	0	Electric shock
30	I-302	31 M	64	175	14	Uremia
31	I-379	42 F	68	170	2	Suicide (barbit poison)
32	N L	5 M	—	—	0	Subdural hemorr (op)
33	I-1239	50 F	—	—	72	Bronchopneumonia
34	II-252	56 M	49	—	25	Pancreatic ca
35	II 255	46 M	—	—	10	Pulm embolism
36	I 1254	41 M	—	—	0	Subdural hemorr
37	I 525	62 M	—	—	0	Myocardial infarction
38	I-553	73 M	—	—	1	Myocardial infarction

were performed within three days after death The subjects utilized represent a largely random selection of the autopsy material available at this institution Efforts were made to limit sampling to subjects up to 60 years of age with a brief period of hospitalization and without suspicion of gross osseous changes in the spine The need to obtain specimens at definite times meant that this delimitation could not always be applied (Table 3 p 64)

It was frequently found that the anterior surface of the disc had been damaged during the autopsy particularly the disc L 5 — S 1 The rejection of segments damaged in this way determined the level from which the samples were taken

Specimens from all the lumbar spines obtained during the period when the present experiments were conducted have been tested consecutively and all of them are included in the results Examinations were made for roentgenographic signs of disc degeneration (Knutsson, 1954 1957) spondylitic spurs anomalies, asymmetrical joint facets or other changes in the vertebrae Only one lumbar segment (no 16 L 4 — L 5) presented appreciable asymmetry of the intervertebral joints Since the mechanical effect of such asymmetry is the subject of much discussion in the literature (Putti 1933 Ghormley, 1933 Wiles, 1935 Guntz, 1937 Ingelmark 1956 Nachemson 1960 Lewin, 1964) a T 12 — L 1 segment (specimen no 19) which displayed such asymmetry was also included No other anomalies were found in the segments presented here Specimen no 19 displayed roentgenographic signs of residual tuberculous spondylitis with partial union L 2 and L 3 The roentgenographic changes are indicated in the master table (Table 4 pp 68—71) and arbitrarily graded

The degree of degeneration in the excised discs was assessed by macroscopic inspection in accordance with established standards (Lindblom 1944 Friberg & Hirsch 1950 Lindblom 1951 Virgin 1951 1958 Naylor & Smare 1951 Ingelmark & Ekholm 1952 Hendry 1958 Nachemson 1960 and others)

Group 0 Macroscopically normal discs without signs of ruptures or other structural changes Both the annulus fibrosus and the nucleus pulposus are shiny white The nucleus appears homogenously gelatinous and is clearly delimited from the annulus fibrosus

Group 1 Discs with a normal appearance in general but with a somewhat more fibrous structure in the nucleus A distinct boundary between nucleus and annulus Some cases present a slight yellowish discolouration (Fig 33)

Group 2 Clear deterioration of the central structures of the nucleus which is definitely drier than normal and usually discoloured There may be

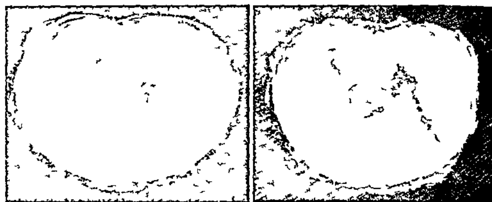


Fig 33 thru 35 Demonstrating various degrees of disc degeneration
a) Spec nr 13 L3—L4 — Degeneration group 1
b) Spec nr 15 L3—L4 — Degeneration group 2
c) Spec nr 13 L5—L1 — Degeneration group 3



isolated fissures in the annulus The boundary between annulus and nucleus is not particularly distinct (Fig 34)

Group 3 Marked degenerative changes in the nucleus as well as the annulus fibrosus, with ruptures and sequestra in the nucleus or the annulus and/or scarring of the nucleus (Fig 35)

Group 0 constitutes healthy discs from generally young individuals while Group 1 represents higher age groups for which the findings may be considered normal

Groups 2 and 3 comprise discs with increasing degrees of degeneration in which hydrostatic conditions cannot be held to be obtained

All specimens were subjected to a varying number of loading series with registration of the displacement at a minimum of 5 measuring points

Some of the senile specimens fractured during the experiment which could not then be concluded according to plan Most of the specimens were subjected to eccentric loading in both the sagittal and the frontal plane Fusion was performed on 33 specimens, other measures being carried out on the remainder

Measurements of intradiscal pressure were recorded for 34 specimens but rejected in the remainder either when the pressure proved not to be reproduceable for the same load in repeated series or because of deviations greater than 5 per cent at calibration before and after the experiment Characteristic data for each specimen and the tests performed are listed in Table 4 (pp 68—71)

Some 1500 loading series with an average of 7 loads per series were conducted on the specimens reported here This makes about 90 000 primary data which together with approximately the same number of calculated values form the basis for the results reported below Some 4000 graphs of the types illustrated provided a satisfactory basis for studying individual specimens but are not suitable for reporting the material as a whole The large quantity of results made it advisable to use a computer However, the number of individuals is relatively small and consequently an analysis of the results should not be based on too many sub groups Specimens are included from children, adults and aged individuals with the age group 40—50 predominating The specimens were classified as normal (gr 0—1) and degenerated (gr 2—3) without otherwise considering the age distribution The risk of osteoporosis increases with age However osteoporotic specimens fractured when still intact' and are thus hardly represented among the fusion cases, for which the strength of the bone tissue is of primary importance

The level of the disc is important in that the range of movement increases in a caudal direction The range of movement is dependent upon the height of the disc and the area of its cross section (Fick 1904) and consideration has been paid to these factors

All the specimens included in this report have contributed to the results for intact specimens and loading *in the* balanced position In the case of eccentric loading on the other hand specimens incorporating more than one segment have been excluded Such specimens buckle in both the sagittal and the frontal plane making it difficult to define the eccentricity of the load

Owing to the variations in the geometry of the different specimens neither the eccentricity nor the load could be predetermined to equivalent figures for comparisons between specimens Such figures can be interpolated graphically with considerable accuracy by combining different

Table 4 — *…on characteristics* / *Tests Performed*

Specimen Nr #	Sex	Age	Disc level tested	Disc degeneration (0–3)	X ray changes (0–3)	Disc area cm²	Sagittal diamete (d_s) mm	Frontal diameter (d_f) mm	Height of disc (h_m) mm	Distance balanced position to geometric center (m_s) mm	Original disc angle in sagittal plane (a_0) degrees	Intact	Devided Ligaments	Screws through facets	Removal of articular processes	Injected disc cm³	Fusion	Fusion type 1–3	Fusion + excised disc	Additional moment	Special tests	Count of series	Max load used kp	Remarks
1	F	44	L2	0	1	12.3	32	47	9	–	−7°	S					S	2	S			6	100	2 segments
2	M	5	L2 }	0	0	7.0	28	32	8.5	–	−6°	X					X							} Pd only
2	M	5	L3 }	0	0	7.1	26	34	8.5	+1	−4°	S F					S	2	S		S	29	64	} One spec
2	M	5	L4 }	0	0	7.6	27	35	8.5	–	−4.5°	X					X							} Pd only
3	M	4	L4 }	0	0	7.4	26	34	9.3	+6	−10°	S F				1.0						45	71	} One spec
3	M	4	L5 }	0	0	8.3	26	36	9.7	−6	−13°	S F		S F							S	45	71	}
4	F	65	L2	2	0	18.5	45	54	10.3	−2	−7.5°	S					S	1	S			10	105	2 segments
4	F	65	L4	2	0	23.0	44	64	15.3	–	−10.5°	S					S	1						2 segments
5	M	65	L1	1	0	19.5	39	58	10.0	−7	−5°	S				S 1.5	S	1	S			24	154	
6	M	40	L4	1	0	23.8	45	66	15.5	−4	−5.8°	S				S 0.5	S	1	S			24	167	
7	M	34	L2	1	0	15.5	39	50	7.3	−2	−2.9°	S					S	2	S			23	200	
7	M	34	L4	1	0	17.8	40	58	10.0	−3	−15°	S	S				S	2	S			10	200	
8	M	74	L4	2	2	16.9	40	53	8.0	−2	−2.7°	S		S		S 3.0						10	170	
9	F	44	L3	1	0	13.4	37	53	12.0	−8	−6°	S F	S	S			S	1(M)				42	200	
9	F	44	L5	1	0	16.9	38	53	12.3	−1	−21°	S F										36	167	

10	F	54	L2	2	0	15 1	38	50	9 0	±0	− 5	S										6	60	
10	F	54	L4	2	0	14 9	36	51	11 3	+5	−11 5°	S								S		10	156	
11	M	64	L2	3	2	17 0	39	58	9 3	−3	− 7 5°	S				(S) L kag						11	120	
11	M	64	L4	3	2	14 0	36	58	10 8	−1	−16 5°	S F								S		23	140	
12	M	68	L4	3	1	19 2	41	60	10 0	−6	−11°	S										1	88	
13	F	53	L1	1	0	11 5	30	39	8 3	−3	− 6°	S F					S F	3	S			30	129	
13	F	53	L3	1	1	16 0	40	42	11 0	−2	− 8°	S F				0 3 F	S F	1	F			30	111	
13	F	53	L5	3	1	16 6	39	50	9 0	±0	−15 5°	S F			S F	(S) Lea kage					F	30	165	
14	M	48	L2	1	0	19 1	41	53	11 7	−2	−11 5°	S F					S F	3	S			24	118	
14	M	48	L4	1	2	19 1	43	56	12 8	−2	−12°	S F					S F	3	S			25	145	
15	M	65	L1	1	1	15 4	38	49	10 3	±0	− 7 5°	S F				(S) 0 9	S F	3	S			25	143	
15	M	65	L3	2	1	17 8	40	52	13 0	−6	− 9 5°	S F				0 8 (F)	S F	3	S F			29	144	
16	M	65	L2	1	1	18 7	41	50	11 3	−2	−10 5°	S F		S F			S	2	S			28	137	
16	M	65	L4	1	2	21 2	46	51	12 0	−2	−17 5°	S F		S F				2	S			42	152	
17	F	70	L1	1	1	9 2	31	40	7 3	−5	− 5 5°	S								S		18	101	
17	F	70	L3	2	1	10 7	31	46	10 0	−8	− 9 5°	S								S		9	130	
18	F	76	L4	2	1	15 0	35	51	11 5	−3	− 8 0°	F										16	161	2 segments
19	M	68	Tn 12	1	2	14 2	36	49	8 0	−4	− 6°	S F			S F	(S) 0 5						17	129	
19	M	58	L2) L3	2	2	20 0	41	59	13 0	−2	− 5 5°	S F	F		S F	(S) 1 0						45	151	Block L2 L3
19	M	58	L5	2	2	24 5	46	57	13 0	−4	−16 5°	S F	S	S		(S) Lea kage	S F	2	S			31	163	
20	M	58	L2	1	1	18 4	40	48	11 3	−5	− 7 3°	S	S	S			S	2	S	S		23	137	
20	M	58	L4	1	1	21 9	44	52	14 0	−3	−10 5°	S F	S F		S F	S 1 8						36	153	
21	F	51	L1	1	1	13 0	36	42	10 7	−4	− 9°	S F			F							14	137	
21	F	51	L3	2	0	20 2	40	49	11 3	−2	− 5 5°	S F					S F	2	S			30	143	

Bold types (S F) ind cate d sc pressure measured

graphs for each specimen This has been done to a considerable extent but would prove excessively voluminous for all the parameters in the entire material For the comparisons which may be said to deal with a behavioural pattern for lumbar spine specimens under the influence of varying forces, practical considerations have led to a grouping of both the loading intensity and the degree of eccentricity The loading intensities were grouped into two intervals, 1 — 2 and 3 — 4 kp/cm² and the eccentricity into 7 equal intervals, from —1 to +1 The higher loading interval corresponds approximately to the individual's total body weight, i e 40 per cent more than the superimposed body weight. The lower loading interval complements this, since many series, particularly those with great eccentricity do not reach the higher load interval, and consequently there tends to be rather limited data for this.

The intervals of eccentricity are natural in relation to the geometric centre of the disc. In the case of the sagittal plane, however, the balanced position is an important factor since it is here that all parameters (except intradiscal pressure) change sign. Only one (degenerated) disc has the balanced position in the interval −0.15 — −0.45 while for 17 healthy and 14 degenerated discs it lies between —0.45 and −0.15 and for 11 healthy and 5 degenerated discs between —0.45 and —0.15

The division of the material into intervals of loading intensity and eccentricity represents a compromise solution to a complex problem It results in an unnecessarily large spread of measurement data and is to be

Table 5

Mean and standard deviation of 48 specimens including two vertebrae and one disc constituting an aggregate motion segment

Disc area (A)	=	[illegible] cm²
Disc height (h_1) posterior	=	[illegible] mm
Disc height ($h_2 = h_4$) lateral	=	[illegible] mm
Disc height (h_3) anterior	=	[illegible] mm

Table 6 *Largest change in angle measured in [illegible] segment*

		Forward	Backward
Sagittal (α)	max.	−7.5	—6.5°
	min	−1.1	—1.5°
		Right	Left
Frontal (β)	max.	−7.6	—6.6
	min.	−1.2	—1.2

accepted only under the above conditions even so, it does not, of course, do full justice to the accuracy with which the measurements were made

All aggregate results are shown in the diagrams as shaded areas representing the standard errors (±SE) of the mean ($\bar{x}$) subgroups are indicated as separate mean and standard errors In the tables the number of measurements (n) are given for each mean

Some specimens prove to be particularly resistant to deformation and were therefore subjected to higher loads at greater eccentricity than was normally the case In the graphs representing results for all the specimens this is reflected by an overrepresentation of such specimens in the extreme intervals of eccentricity In some intervals, for which only a few measurements were obtained, the general picture is liable to be distorted by extreme results for individual specimens These specimens could of course have been excluded but it was decided instead to give free rein to chance and to discuss the reason for such deviations in each case

IV Results and discussion

Intact specimens

Motion centre

Joint function is usually described in anatomy as rotation around and translation along the body's three mutually perpendicular, primary axes the longitudinal, sagittal and transverse A lumbar motion segment (two vertebrae with the intermediate disc and ligaments) is considered to possess six degrees of freedom, i e both rotation and translation are represented (Broman & Hjortsjo, 1952) It has been held that all the axes of motion pass through the centre of the nucleus pulposus (Fick, 1904, Strasser, 1913, Calvé & Galland, 1930, Hagelstam, 1949, Broman & Hjortsjo 1952) though with varying instantaneous centres (Dittmar, 1931) In the event of disc degeneration, the frontal axes of motion is reported to be displaced dorsally towards the intervertebral joints (Gianturco 1944, MacNab, 1950) Knutsson (1944) considers that increased sagittal translation is an early sign of disc degeneration

In accordance with the principle stated on pp 22 and 52 (Hoag, 1960) the position of the instantaneous centres has been calculated at rotation in the sagittal and frontal plane With this procedure, translation along the longitudinal axis (compression of the disc without accompanying rotation or translation along the other main axes) gives an instantaneous centre with an infinite x coordinate Similarly for translation in the horizontal plane the y coordinate is at infinity It follows that the position of the instantaneous centre is discontinuous for central loading Fig 36 illustrates the position of the instantaneous centres in rotation in the sagittal plane (around frontal axes) for five specimens representing different levels of the spine and different degrees of disc degeneration Hoag s statement is confirmed to the extent that healthy discs show a concentration of instantaneous centres for ventroflexion in the dorsal part of the disc and vice versa The degenerated discs give a very large spread and many of their values lie outside the figure At rotation in the frontal plane (Fig 37) there is a corresponding tendency for the instantaneous centres to be concentrated to the left of the median for flexion to the right and vice versa but in this case even normal discs display a wide spread The spread

disc center

Dorsal Ventral

3 1

Spec. N
13 L5-L1
15 L3-L4
23 L2-L3
24 L3-L4
30 L4-L5

Fig 36
Pos t ons of momentary cent a at motion in sag ttal plane
Normal discs. flexion □, extension O
Degenerated discs flex on ■ extens on ●

meas ring plan

Disc

left right

measuring plane

Disc

Fig 37
Pos t ns of m ment ry ent a at late al bending Normal d'scs, right hand □ left hand bending O
Degenerated d scs ght hand ■ left hand bending ●

6

Fig 39
Specimen
Nr 20
L2–L3
Change in angle (α) of the Seg ttal plane under constant load at different excentric t es
Intact specimen

Ecc ntricity
+20 mm
+10 mm
c C
10 mm
-20 mm
change of angle α^0
$+4^0$ 3^0 2^0 1^0 $+1^0$ $+2^0$ $+3^0$ $+4^0$
10 kp
25 kp
50 kp
100 kp
150 kp

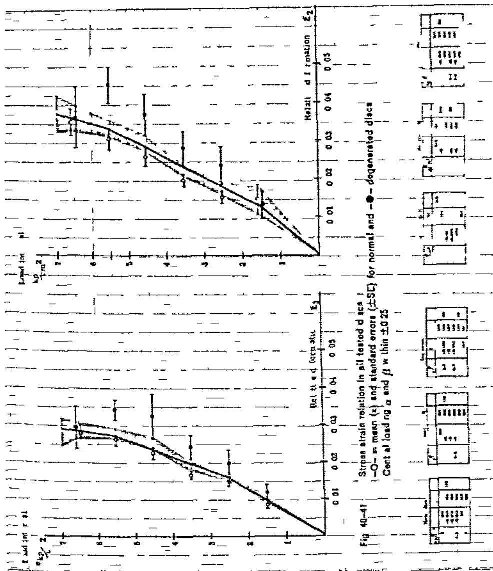


Fig 40–41 Stress strain relation in all tested discs —O— = mean (x) and standard errors (±SE) for normal and —●— degenerated discs Central loading α and β within ±0 25

of such a test on a specimen with class 1 degeneration is shown in Fig 42 The sagittal and frontal diameters both increased by 1 3 mm in the loading interval 1 — 2 kp/cm² and by 2 mm in the interval 3 — 4 kp/cm² The increase was the same for centric and excentric loading In the two highly degenerated discs the increase was smaller in the sagittal diameter but somewhat larger in the frontal. These discs bulged considerably even before loading while during loading it was obvious to the naked eye that they bulged more in some parts of the periphery than in others The magnitude of the bulging was very similar to that reported by Hirsch &

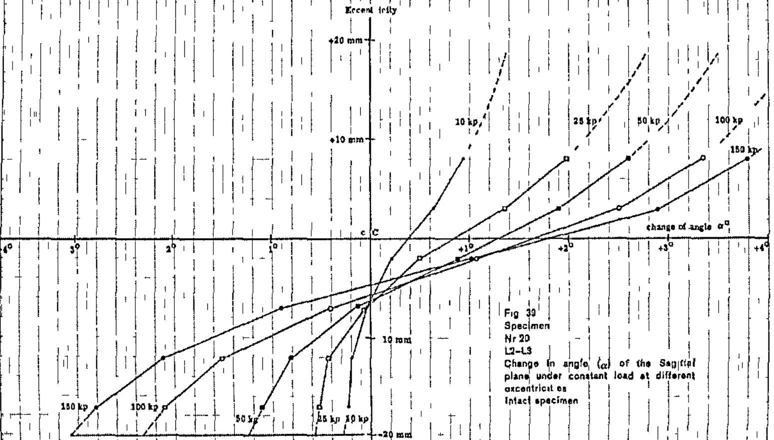


Fig 30
Specimen
Nr 20
L2–L3
Change in angle (α) of the Sagittal plane under constant load at different excentricities
Intact specimen

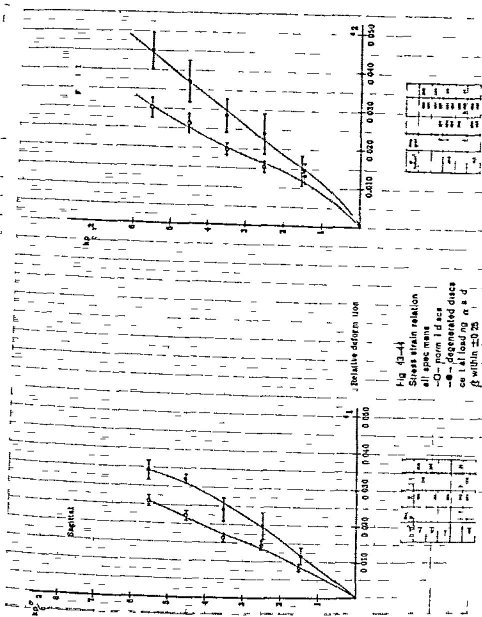


Fig 43–44
Stress strain relation
all specimens
—O— normal discs
—●— degenerated discs
ce t at loading α ≠ d
β within ±0.25

The vertical deformation is statistically larger for the degenerated than the normal discs at all loading intervals (Figs 43 and 44) at the 1 per cent level (Student s T test) This greater compressibility also results in a larger residual deformation after the first series of loadings After repeated loadings however the residual deformation is equally large in healthy and degenerated discs The residual deformation in 52 intact specimens after the first and last series of loadings is given in Table 7 (in the case

Table 7
Residual deformation of the disc after the first and last loading serie on intact specimens

Serie	Degree of degeneration	Mean for $\frac{\delta_{1v} + \delta_{3v}}{2}$	SE	n
First	0 — 1	0 065	± 0,015	33
„	2 — 3	0 119	± 0 025	19
Last	0 — 1	0 155	± 0 033	33
„	2 — 3	0 156	± 0 006	19

of the remaining specimens, the displacement gauges were zeroed between the first and the last series of loadings)

As much Chromopaque or Ringer solution as possible was injected into 25 discs (see Table 4, p 68) The maximum amount varied between 0 3 and 3 cc except in the case of eight discs which leaked There was practically no resistance to the injection, which caused the average height of the disc to increase approximately in relation to the volume injected at the same time, the bulging of the disc was reduced (roughly measured with calipers) The maximum amount which could be injected was reached abruptly, without any gradual increase in resistance to the injection The height of the disc could not then be further increased, even though maximum force was applied to the injection On the other hand the discal pressure varied synchronously with the injection force The maximum intradiscal pressure measured during injection was 3 5 kp/cm When injected specimens were loaded vertically, the horizontal displacement was reduced (cf Radberg 1954) but the initial compression and the residual deformation were large, indicating that the injected fluid had spread in the disc and/or been pressed out of this When the discs were sectioned, the contrast medium was seen to have collected in what appeared to be preformed cavities (Teichert, 1962a, 1962b), which in normal discs were situated symmetrically and centrally (chromopaque has a large molecular diameter of one micron) Degenerated discs having irregular cavities and concentric or radiating fissures were accordingly stained with contrast medium

Since the injection of contrast fluid changes the physical properties in the disc, discography could not be used as a routine in the present investigation but was performed after the other measurements on the disc had been concluded

Rotation-torque

Four specimens were used for this test (no 24 L 3 — L 4 and L 5 — S 1, no 31 L 3 — L 4 and L 5 — S 1) A threaded bolt, 10 cm long, diameter 6 mm

was screwed horizontally through the upper vertebral body parallel to the sagittal diameter The specimen was placed in the loading apparatus with the displacement and pressure gauges applied in the usual way A sagittal horizontal displacement gauge was fitted against measuring point 2 (the extensometer over the vertebra was omitted) Thin steel wires were then attached at either end of the bolt, 45 mm from the centre of the vertebral body, and pulled horizontally in opposite directions parallel with the frontal diameter Each wire was hung vertically over a pulley and loaded with 4 kg which gave a positive moment of 36 kpcm acting around the longitudinal axis The angle of rotation (γ) was read of the compression apparatus' protractor and was also calculated from the equation $\tan \gamma = 2 \frac{(\delta_{1h} - \delta_{1})}{d_f}$ (6)

The angles of rotation calculated in this way for the four discs were 0 33, 0 33 0 54 and 1 18° (simultaneous central vertical loading reduced α) After removal of the intervertebral joint facets, the angle increased to 1 0 2 3, 1 7 and 2 3° respectively Fick (1904) gives the average for intact, lumbar segments as 2 5° Andersson & Ekstrom (1940) found 0 6° at a torque of 48 kpcm and 1 9° at 200 kpcm In the present study the accompanying change in angle of the horizontal plane was negligible The calculation assumes that the rotation occurs around the longitudinal axis through the centre of the disc this seems resonable Although the measurements incorporate certain uncontrollable errors, they do indicate the magnitude of the possible rotation and show that the intervertebral joints take up torque in the horizontal plane

An interesting phenomenon probably associated with the helicoidal arrangement of the fibres in the annulus is that the average height of the disc increases when horizontal torque is applied — an increase that is approximately proportional to the degree of rotation At the same time the disc pressure dynamometer gave a negative reading

Frontal and sagittal axes

Translation in the horizontal plane

Fick (1904) asserts that parallel displacement between vertebrae is severely limited but not entirely prohibited by the construction of the annulus Brocher (1958) considers that a parallel displacement between vertebrae always indicates a pathological change of major clinical significance Severin (1943) demonstrated roentgenologic retroposition in 50 per cent of degenerated discs Knutsson (1944) developed a test of stability by using lateral X-rays at maximal flexion and extension More than half of

58 discs with anatomical signs of degeneration showed 'instability Displacement in the direction of flexion was presented by 26 and in the opposite direction by four (paradoxical mobility according to Gianturco, 1944, Schalimtzek, 1958) In 18 cases Knutsson found roentgenologic instability out of 82 without other anatomical signs of disc degeneration He considered this to be an early roentgenologic sign of disc degeneration. A similar investigation on spinal specimens was made by Friberg & Hirsch (1949), who correlated the X-ray findings with the pathological anatomy of the intervertebral discs Hagelstam (1949) found that in roentgenologically normal discs the limits for parallel displacement were ±2 mm while they were wider for degenerated discs but seldom more than 3 mm He found that the error of measurement for roentgenological methods can easily amount to 1 mm Direct measurements on specimens do not seem to have been made previously

In the present investigation the parallel displacement is given as the x-coordinate of the measuring point No specimen at any load or eccentricity gave a displacment of more than ±2 mm, while only a few results exceded ±1 mm Various initial angles of the vertebral bodies in relation to the horizontal plane (v_1 and v_2 ±10°) did not influence the magnitude *of the horizontal displacement The direction of this displacement was* liable to vary for loads near the centre but otherwise it followed the direction of rotation, so that positive rotation gave a positive horizontal displacement Increased eccentricity resulted in increased horizontal displacement but could be achieved near maximal displacement with slight loads, suggesting that there is a certain play in the unloaded disc in the horizontal direction With considerable eccentricity however, there is a critical load for each disc at which the horizontal displacement reaches a certain maximum and then might change its direction upon further loading In Figs 45 and 46, points 1 and 2 represent motion in the horizontal plane for varying eccentricity and loads of 1—2 and 3—4 kp/cm² For an eccentricity of —0 45 to —0 15 in the sagittal plane the horizontal displacement is 0, increases and decreases linearly respectively at the neighbouring eccentricity intervals but curves away at greater eccentricities to a maximum at +0 45 to +0 75

Parallel displacement along the frontal axis (Fig 46) is of the same magnitude as in the sagittal axis

The horizontal displacement is not to be regarded as an isolated motion but as an integrated function of the disc s deformation by the forces acting upon it Fig 47 shows a typical case of the relationship between the horizontal and vertical displacements of point 1 at different loads and eccentricities

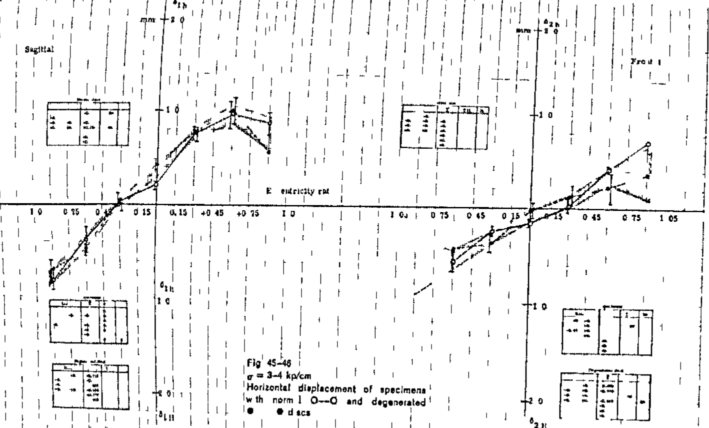


Fig 45–46
σ = 3–4 kp/cm
Horizontal displacement of specimens w th norm l O—O and degenerated ● d scs

58 discs with anatomical signs of degeneration showed instability Displacement in the direction of flexion was presented by 26 and in the opposite direction by four (paradoxical mobility according to Gianturco, 1944, Schalimtzek 1958) In 18 cases Knutsson found roentgenologic instability out of 82 without other anatomical signs of disc degeneration He considered this to be an early roentgenologic sign of disc degeneration A similar investigation on spinal specimens was made by Friberg & Hirsch (1949) who correlated the X-ray findings with the pathological anatomy of the intervertebral discs Hagelstam (1949) found that in roentgenologically normal discs the limits for parallel displacement were ±2 mm while they were wider for degenerated discs but seldom more than 3 mm He found that the error of measurement for roentgenological methods can easily amount to 1 mm Direct measurements on specimens do not seem to have been made previously

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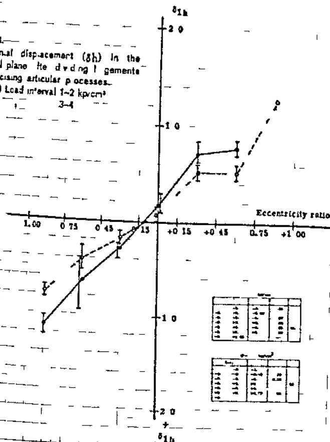


Fig 48. Horizontal displacement (δh) in the sagittal plane after dividing ligaments and excising articular processes.
O—O Load interval 1–2 kp/cm²
● — ● 3–4

measuring point and the change of the angle in the plane Motion in the sagittal plane is thus represented by ε_1 and α and motion in the frontal plane by ε_2 and β It should be borne in mind that, by definition, positive rotation (forward flexion and lateral bending to the right) is indicated with a positive sign for the change in angle (given in radians) while the deformation is described as negative when the distance between a measuring point and its reference point diminishes and positive when this distance increases For a correct conception of the movement each point on the deformation curve must be compared with the corresponding change in angle

Figs 49 a and 50 a illustrate rotation in the sagittal plane (dorsoventral flexion) The change in angle is 0 at an eccentricity of −0 12 i e a distance (m_0) of 4 5 — 5 mm dorsal of the geometric centre The relative deformation is then 3 ± 0 3 per cent which corresponds to a deformation

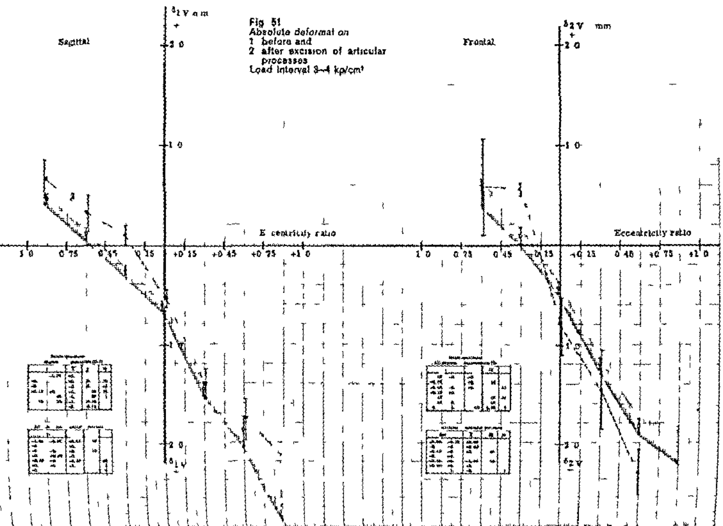


Fig 51
Absolute deformation
1 before and
2 after excision of articular processes
Load interval 3–4 kp/cm²

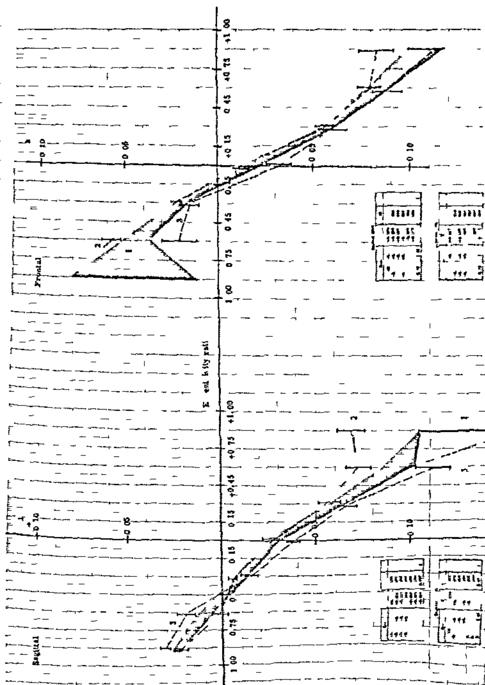


Fig. 52. Load interval 1–2 kp/cm
R l ti e d f rm t n ntact p c m
1 All p cim
2 Degenerated d s s
3 Normal d scs

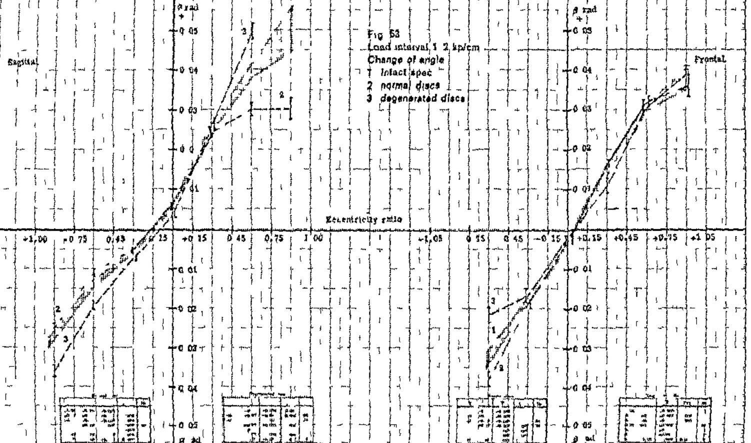


Fig 53
Load interval 1 2 kp/cm
Change of angle
1 Intact spec
2 normal discs
3 degenerated discs

of 0.5 ± 0.04 mm in absolute figures (cf Fig 51 a) For an increasing negative moment, the change in angle shows an almost linear regression line with only a slightly larger change for degenerated than for healthy discs For a positive moment the curve for healthy discs flattens out at about 0.05 radians while that for degenerated discs again shows an almost linear increase in angle with a mean twice as large at that for healthy discs at the ultimate moment The relative deformation shows a completely analogous course that for healthy discs having the same tendency to level out at the maximum positive moment. The individual specimens contributing the measurements in the interval + 0.75 — + 1 show, however that an increased moment always gives increased deformation thus the aggregate curve exaggerates the position at the maximal moment (cf p 72) The pattern for deformation and change of angle is the same in principle for the loading intensity 3 — 4 kp/cm and 1 — 2 kp/cm² (Figs 52 and 53)

Rotation in the frontal plane (lateral flexion) is presented in the same way in Figs 50 b and 49 b by the change of angle in the frontal plane (β) and the relative displacement of the right hand measuring point (ε) The change in angle gives a gently S shaped curved with healthy discs tending to show a somewhat larger change than degenerated discs The balanced position of the healthy discs is displaced slightly to the right of the centre (approx 0.7 per cent), with a relative deformation of 4.5 ± 0.6 per cent that for the degenerated discs being 5 ± 0.6 per cent Loading at the eccentricity interval +0.45 — +0.75 results in a compression of the disc at point 2 by approximately 13 per cent, while the stretch at the same point with the same negative moment is approximately 5 per cent or in absolute figures — 1.8 mm and + 0.5 mm The increase in the height of the disc on one side is thus only one third of the decrease on the other Fig 54 illustrate the discal pressure at different eccentricity intervals in the sagittal plane The data for pressure during lateral flexion are widely dispersed with extreme values for individual specimens which upset the general picture On would expect lateral flexion to give a symmetrically shaped curve There does not seem to be any difference between healthy and degenerated discs which is natural in view of the selective nature of the measurements Nachemson (1960) has reported hydrostatic behaviour of the nucleus pulposus which was not influenced by moderate degeneration (corresponding here to groups 0 1 and 2) and states that the intradiscal pressures are on average 30 — 50 per cent higher than the applied load per unit area The level of the disc in the lumbar spine did not influence these results He has also demonstrated (Nachemson 1963) that compression of the specimen between angled

The motion of the segment (the discs — and the vertebral body s — deformation) can be visualized in terms of a section along one main plane, with the forces acting in this (Figs 56 and 57) Since the system is *statically indeterminate, the distribution of forces in the section* must be visualized in model form, with the arrows representing the tension in the annulus fibrosus anterior and posterior circumference (p_1 and p_3) *the nucleus on either side of the centre (pn_1 and pn) and the ligamentum* flavum (p_6) together with the external load on the disc (P) and any additional load (P_5) Every external load, centric or eccentric elicites a thrust and a new position of equilibrium Thrust is elicited, however in

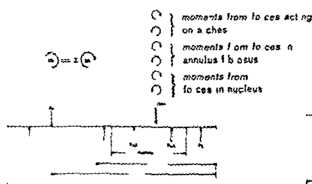


Fig 56
Simplified vector analysis of intact specimen when *loaded centrally*

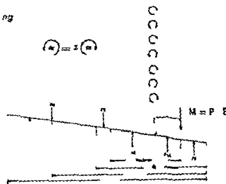


Fig 57
Simplified vector analysis of intact specimen *when loaded eccentrically*

the vertebrae as well (cf p 62) and their geometry and composition further complicate the picture

Fig 38 illustrated how a small force applied to the spinous process resultec in a relatively large change in angle in the unloaded disc (+1 5°) In t *specimen described in Fig 58 the force in the spinous process* gradually increased from 0 to 10 kp $\alpha = 1\ 5$ was first recorded in disc at a flexion moment of 45 kpcm in the centre of the disc, com with 12 kpcm in specimen 17 This difference may, however be attr to the discrepancy between the dimensions of these specimens (se 4 p 68) The change of angle (α) is plotted in Fig 58 as c according to the normal method (formula 2b, p 52) as well as to formula 2a to show the deformation in the vertebral arch *As shown the rotation in the sagittal (and the frontal) pla* linear function of the moment but has a characteristic S curve of which is related to the moment as well as to the ve This is further illustrated in Fig 39 which is made up of *for one specimen with several loads It will be seen more cle*

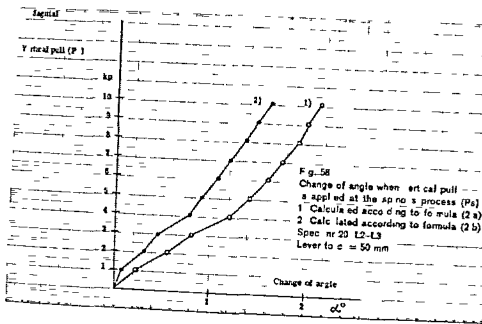
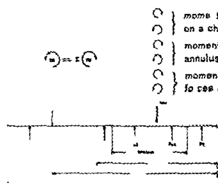


Fig. 58
Change of angle when vertical pull is applied at the spinous process (Ps)
1 Calculated according to formula (2 a)
2 Calculated according to formula (2 b)
Spec nr 20 L2–L3
Lever force = 50 mm

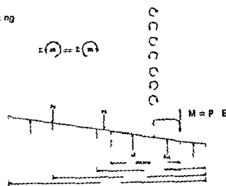
discs resists extension more than flexion and that this resistance increases with the eccentricity of the load This must be because the annulus fibrosus is compressed under increasing resistance so that an increasing moment gives a tendency to the opposite direction of rotation Since the disc is lower dorsally than ventrally, the moment acting in the direction of rotation increases more rapidly during dorsiflexion The effect can also be reinforced by the horizontal displacement and by the annulus bulging on the compressed side and being stretched on the other so that the disc's centre of gravity is displaced in the direction of rotation

The stabilizing effect of the dorsal elements was studied by applying positive eccentric loads and cutting the supraspinous and interspinous ligaments the ligamentum flavum and the joint capsules one by one Only the ligamentum flavum was found to have any restrictive effect within the range of movement tested Removal of the intervertebral joints did not lead to any further increase in the range of movement Nor did the asymmetric intervertebral joints appear to impede movement in either the sagittal or the frontal plane. The combined results for these specimens thus illustrates the effect of cutting the ligamentum flavum (Figs 59 *a* and *b* and 60 *a* and *b*) The balanced position appears to have been displaced towards the centre There is a tendency not significant, to an increased change of angle for both positive and negative eccentricity and to the corresponding change in the ventral height of the disc In the frontal plane too there is the same small tendency for the angle to increase

The motion of the segment (the discs — and the vertebral bodys — deformation) can be visualized in terms of a section along one main plane, with the forces acting in this (Figs 56 and 57) Since the system is statically indeterminate, the distribution of forces in the section must be visualized *in model form with the arrows representing the* tension in the annulus fibrosus anterior and posterior circumference (p_1 and p) the nucleus on either side of the centre (pn_1 and pn) and the ligamentum flavum (p_v) together with the external load on the disc (P) and any additional load (P_5) Every external load, centric or eccentric, elicites a thrust and a new position of equilibrium Thrust is elicited, however, in



F g 56
S mpl f ed vecto analys s of intact specimen when loaded centrally



F g 57
S mpl f ed vector analysis of intact spec men when loaded eccentrically

the vertebrae as well (cf p 62) and their geometry and composition further complicate the picture

Fig 38 illustrated how a small force applied to the spinous process resulted in a relatively large change in angle in the unloaded disc (+1 5°) In the specimen *described in Fig 58 the force* in the spinous process was gradually increased from 0 to 10 kp $\alpha = 1\,5$ was first recorded in this disc at a flexion moment of 45 kpcm in the centre of the disc, *compared* with 12 kpcm in specimen **17** This difference may, however be attributed to the discrepancy between the dimensions of these specimens (see Table 4 p 68) The change of angle (α) is plotted in Fig 58 as calculated according to the normal method (formula 2b, p 52) as well as according to formula 2a to *show the deformation* in the vertebral arch

As shown the rotation in the sagittal (and the frontal) plane is not a linear *function* of the moment but has a characteristic S shape the curve of which is related to the moment as well as to the vertical force This is further illustrated in Fig 39 which is made up of such graphs for one specimen with several loads It will be seen more clearly that the

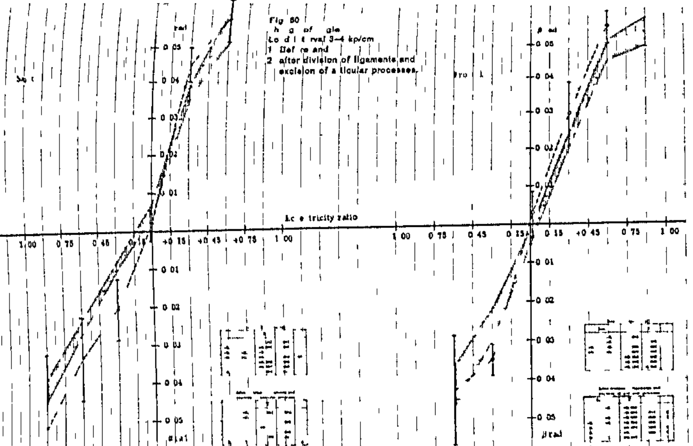


Fig 60
h g of gle
Lo d I t rval 3–4 kp/cm
1 Bef re and
2 after division of ligaments and excision of a ticular processes.

Fig 59
Load interval 3–4 kp/cm
absolute deformation (δV)
1 In intact spec and after
2 D v sion of ligaments and excision of art cular p ocesses

Sagittal

Frontal

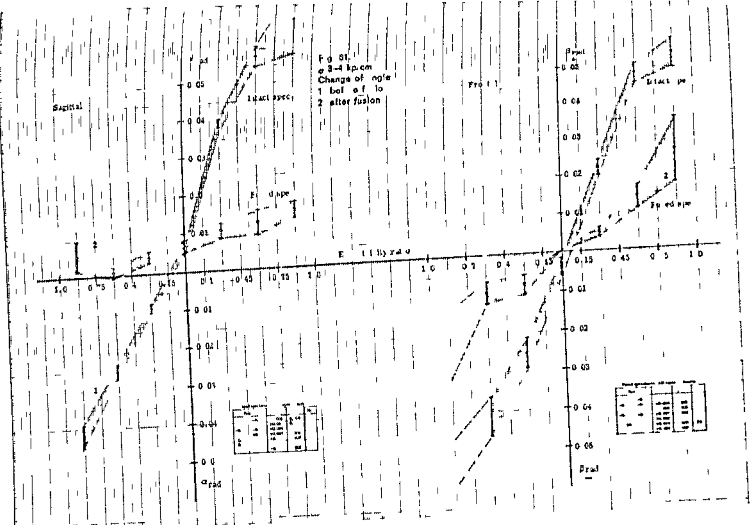
$\delta_1 V$ +2 0, 1 0, 1 0, 2 0 $\delta_1 V$

$\delta_2 V$ +2 0, 1 0, 1 0, 2 0 $\delta_2 V$

Eccentricity ratio

1 00, 0 75, 0 45, 0 15, +0 15, 0 45, +0 75, +1 00

1 00, 0 75, 0 45, 0 15, 0 15, +0 45, +0 75, +1 0


Sagittal
0 05
0 04
0 03
0 01
1,0
0 4
0 1
0 43
1 0
0 01
0 03
0 0
α_{rad}
β_{rad}
0 05
0 04
0 03
0 02
1 0
0 7
0 4
0 43
0 15
0 5
0 01
0 02
0 03
0 04
0 06
2 after fusion

The effect of fusion

Fusion was simulated with plastic casts as described above (p 33) A total of 33 lumbar interspaces in 32 specimens were fused Type 1 fusion (between the spinous processes) was performed on 9 specimens, type 2 (including the intervertebral joints) on 17 and type 3 (including the transverse processes) on 6 specimens The results are reported along the same lines as for the intact specimens The effect of fusion on the pattern of motion is of quite a different order than the relatively small differences between specimens with degenerated and normal discs Consequently the fused specimens have not been sub divided according to the degree of disc degeneration For the sake of comparison the diagrams below thus include the corresponding curves (shaded areas) for all intact specimens

Posterior fusion in general

Figs 61*a* and *b* show the change of angle in the sagittal and frontal planes for different eccentricity intervals at loads of 3 — 4 kp/cm In the sagittal plane, the average change of angle is positive for both negative and positive eccentricity There is a steady increase in a positive direction from the largest negative eccentricity When loading over the geometric center of the disc, the change of angle is equally large for fused and intact specimens but at the largest positive eccentricity the change of angle after fusion is only 20 per cent of that for intact specimens

Measurements are lacking for the extreme eccentricites during lateral flexion For central loading however, there is no spread of the measurements indicating that this interval of eccentricity falls within the width of the fusion so that loading in this region does not give rise to any *rotating moment in the frontal plane Increased eccentricity results* in symmetrically increasing rotation in both a positive and a negative direction

Figs 62 *a* and *b* and 63 *a* and *b* show the relative (ε) and *absolute* (δ_v) deformation at points 1 and 2 As in the case of the change of angle ε_1 displays only negative values which rise continuously as the load is moved in a ventral direction i e as the moment in relation to the fusion increases The eccentricity interval + 0 75 to + 1 has a preponderance of type 3 fusion hence the misleading curve of the graph Central loading gives almost the same deformation for both intact and fused specimens

For lateral flexion and positive eccentricity the deformation at the right hand measuring point after fusion is approximately half that with intact specimens With negative eccentricity ε_v (and δ) is positive but the total deformation in a positive direction is only one-third of that for intact

Fig 83
Absol te defo m ti n (δy)
1 befo and
2 after fusion
(L ad terval 3–4 kp/cm²)

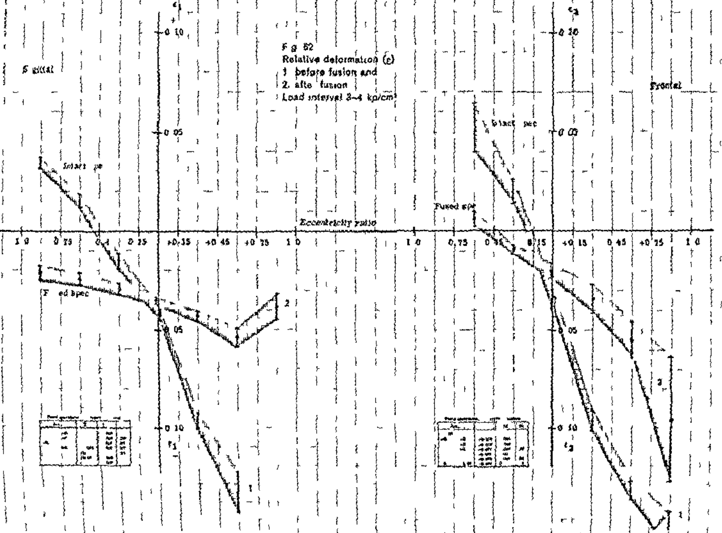


Fig. 52
Relative deformation (ε)
1 before fusion and
2. after fusion
Load interval 3–4 kp/cm²

Fig. 63
Ab l la def m tion (δy)
1 b fo e and
2 after f s on
(Load Interval 3–4 kp/cm²)

Sagittal

F ont 1

Intact spe

F d spe

F e d pe

Ecce t i ity ratio

$\delta_1 V$

$\delta_2 V$

1 0 0 7 0 45 0 15 +0.15 0.4 +0.75 1 0

1 0 0 75 0.45 0.15 0 15 0 45 0 75 1 0

2 0 1 0 1 0 2 0

specimens At central loading the compression after fusion is considerably less than with intact specimens, unlike the finding for loading in the sagittal plane This is because central loading after fusion always gives a positive value for the angle α, so that the top plate of the specimen angles forward against the sagittal horizontally positioned loading edge This means that the resultant of the loads in the frontal plane lies somewhat dorsal of the centre, reducing the sagittally rotating moment

The effect of fusion on the intradiscal pressure is shown in Fig 64 The pressure is considerably less after fusion with negative eccentricity, i e loading near the fusion, and increases gradually as the load is moved ventrally and the moment is thereby increased For large positive moments the intradiscal pressure may be greater at the same load after fusion than for the corresponding intact specimen Fig 65 shows the quotients for the discal pressure after fusion divided by that in the same intact specimens at the same load. Thus, a quotient of 1 indicates that the pressure was the same before and after fusion while quotients greater than 1 indicate that the fusion led to an increase in intradiscal pressure On an average, there was a reduction by 50 per cent In 21 comparable series of intact and fused specimens the intradiscal pressure remained unchanged or increased after fusion

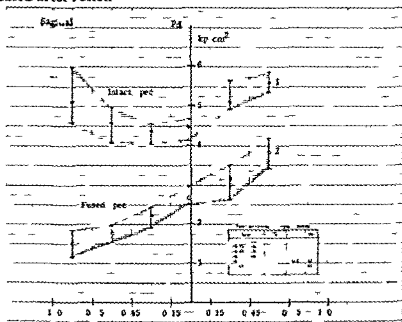
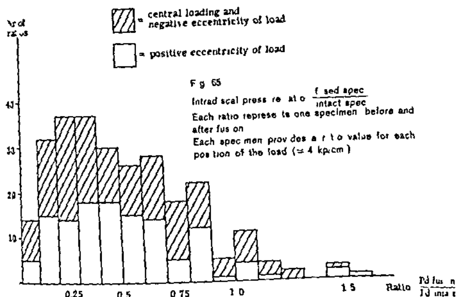


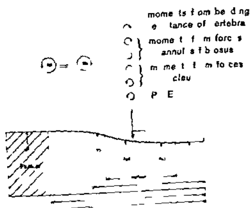
Fig 64
Intradiscal pressure (Pd)
1 before fusion
2 after fusion
Load interval 3–4 kp/cm



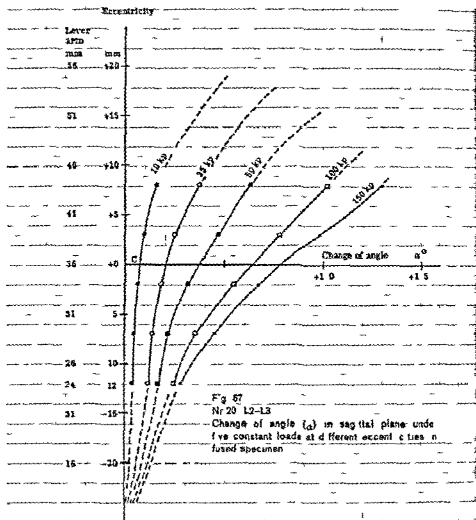
F g 65
Intrad scal press re at o f sed spec / intact spec
Each ratio represe ts one specimen before and after fus on
Each spec men prov des a r t o value for each pos tion of the load (= 4 kp/cm)

Posterior fusion according to method

The individual vertebra in a fused segment may be regarded as a beam clamped at one end (the arch) and with the other end (the vertebral body) resting on several deployed supports As already mentioned, the system is statically indeterminate and consequently the distribution of forces cannot be calculated As a working model however one can visualize the moment acting in the sagittal section (Fig 66) The only difference in principle between the three types of experimental fusions is in the distance between the clamp and the support In other words a central load on the vertebral body results in the greatest bending moment in type I



F g 66
S mpl f ed ctor analys s f f sed pec m n



F g 67
Nr 20 L2–L3
Change of angle (α) in sag ttal plane unde f ve constant loads at d fferent eccent c ties n fused specimen

fusions and the least in type 3, type 2 lying somewhere between these two Since it has been shown (Fig 32 and 58) that a vertebra is quite deformable, it is clear that the relatively long unsupported part of the "beam in type one fusion permits a change of the angle in both a positive and a negative direction The possibility of negative rotation diminishes the further the extension of the fusion in the ventral direction The system is visualized in Fig 66 showing arbitrary resultant forces and moments for the various supporting surfaces The fixation in the fusion is accounted for by a force upwards (the thrust) and a (negative) clamping moment

Fig 67 shows the change of angle in the sagittal plane during constant loads on a fused specimen (type 2) at different eccentricities Fig 68 shows the results for loading after excision of the disc Once the disc has been removed the vertebra can obviously offer little resistance to bending



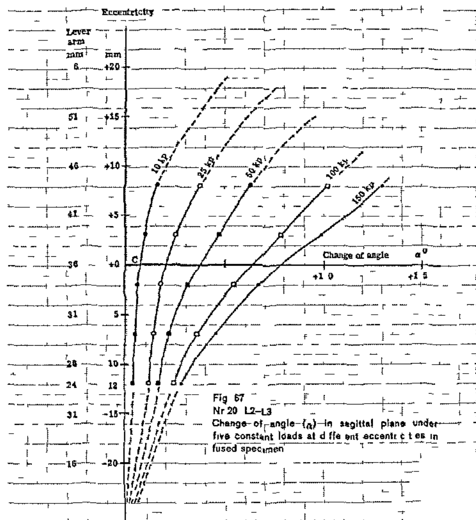


Fig 67
Nr 20 L2–L3
Change of angle (α) in sagittal plane under five constant loads at different eccentricities in fused specimen

fusions and the least in type 3, type 2 lying somewhere betw
Since it has been shown (Fig 32 and 58) that a vertebra is
it is clear that the relatively long, unsupported part of the
one fusion permits a change of the angle in both a positive
direction The possibility of negative rotation diminishes
extension of the fusion in the ventral direction The sy
in Fig 66 showing arbitrary resultant forces and
supporting surfaces The fixation in the fusion is
upwards (the thrust) and a (negative) clamping
Fig 67 shows the change of angle in the sagittal
loads on a fused specimen (type 2) at different
shows the results for loading after excision of the
been removed, the vertebra can obviously offer little

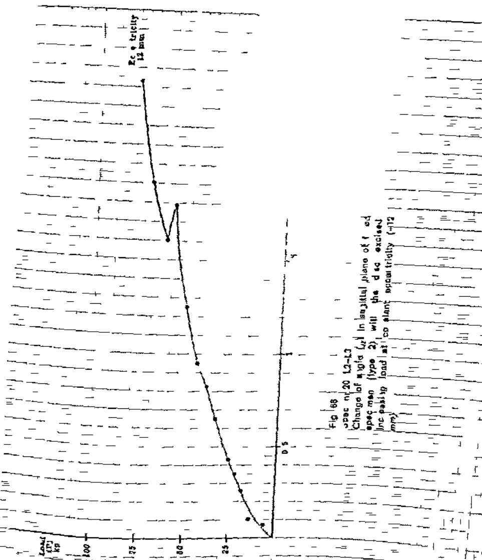


Fig 68 Spec nr 20 L2–L3 Change of angle (γ) in sagittal plane of fused specimen (type 2) with the disc excised Increasing load at eccentricity (+12 mm)

The stability of a segment after fusion is thus still highly dependent upon the load carrying capacity of the disc Compared to the intact specimen (Fig 39) the resistance to bending with negative eccentricity is extremely large at all loads but diminishes gradually as the load is shifted ventrally Within the range of loads applied the regression is steeper throughout after fusion than for intact specimens On the other hand the change of angle with increasing load tends to diminish for intact specimens but to accelerate after fusion Thus the intact specimen is characterised by the disc s increased rigidity with increasing loads while the fused specimen is characterised by the elastic change in the bone

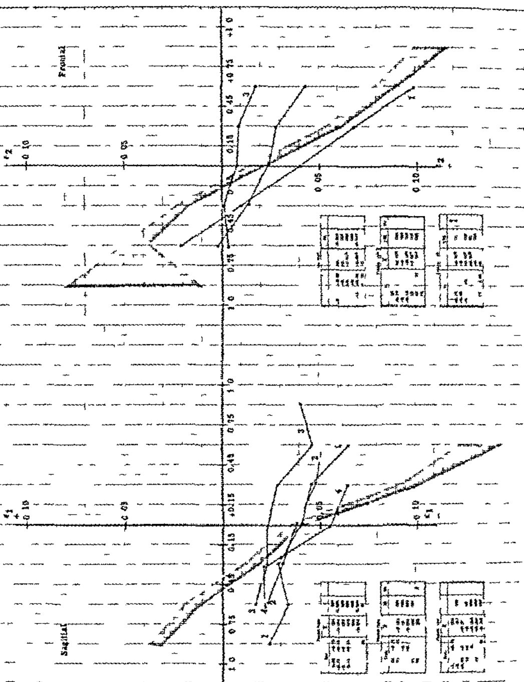


Fig. 69
Relative deformation (ε)
1 Fusion type 1
2 " 2
3 " 3
4 Screws through intervertebral joints
Load interval 3–4 kp/cm²

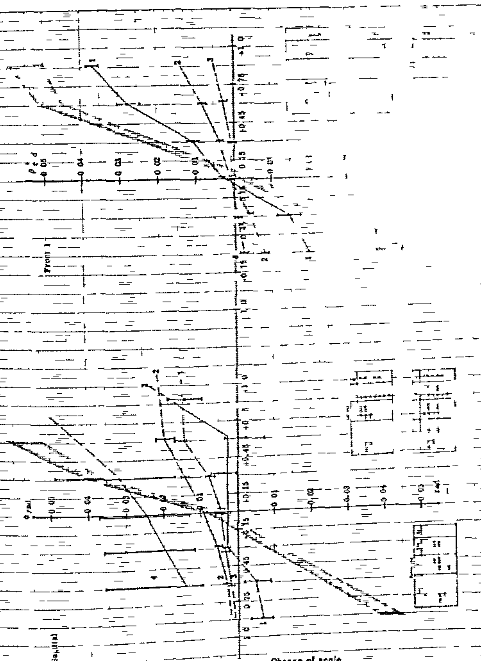


Fig.
Load interval σ 3–4

This brings us to a consideration of the effect of different types of fusion Figs 69 and 70 show the relative displacement at point 1 and the change of angle in the sagittal plane Type 1 fusion results in a considerable depression of the disc s ventral circumference for positive as well as negative eccentricity, but the deflexion accelerates towards the extremes Accordingly, the angle changes only a little during loading around the central position and it is only at the extreme eccentricities the tendency to rotation increases rapidly in both a negative and a positive direction Type 3 fusion displays a considerably greater stability with respect to both vertical displacement and change of angle, while positive rotation occurs even at maximum negative eccentricity As already mentioned type 2 fusion represents an intermediate condition

For loading in the frontal plane, the compression with centric loading is considerably greater after type 1 fusion than in intact specimens, while during eccentric loading the depression and elevation of point 2 is almost as large as in intact specimens and the angle change is only slightly smaller

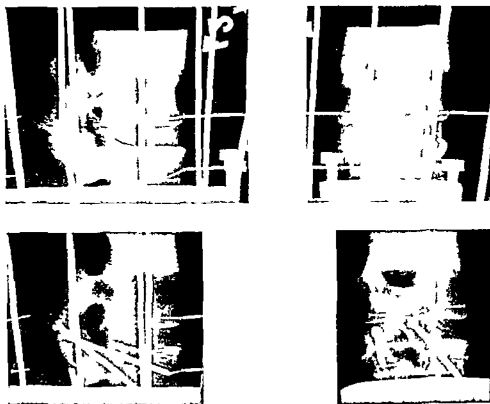
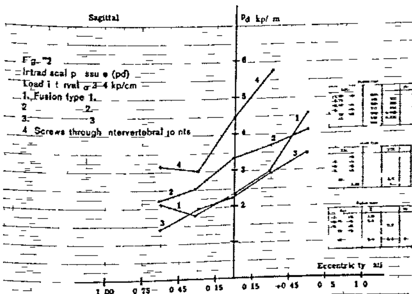


Fig 71 (a—d)
Roentgenograms of spec nr 16 L2—L3 fixed in the loading apparatus (a b) intact specimen (c d) specimen with long screws through the intervertebral joints

Type 3 fusion on the other hand, shows very sl p ... o for positive eccentricities — still negative at m... city The change in angle gives a symmetric... e small both positively and negatively

In 8 specimens (including one comprising several ... joints were fixed with screws instead of a pl... this results in an upward thrust but no (c... moment The screws exert a certain stab... centricities but at positive eccentricities the r... to those for the intact specimen There a ... the introduction of the screws resulted in a poi... c... between the specimens in other words, th s spread ... a major difference in behaviour

The intradiscal pressure for different types of fusion ... fixed with screws through the intervertebral joints shown in Fig 7... There is a tendency for the pressure to increase from negative to positive eccentricity The curve for type 1 fusion is low initially because this relatively unstable fixation gives the disc a greater chance of balancing the forces produced Both here and with screws through the intervertebral joints however the intradiscal pressure increases rapidly at maximum positive eccentricity and reaches or exceeds the level for the intact specimens



Specimens comprising more than one motion segment

As already mentioned, the pattern of deformation for specimens incorporating several discs is too complex to permit direct comparisons between specimens. The differences between the specimens are mainly ascribable to differences in the geometry of discs and vertebrae and the number of segments included. The pattern of deformation for the 8 specimens in this series, illustrated here by two examples, revealed no differences in principle.

Specimen no 29 from an adult individual with normal discs comprised

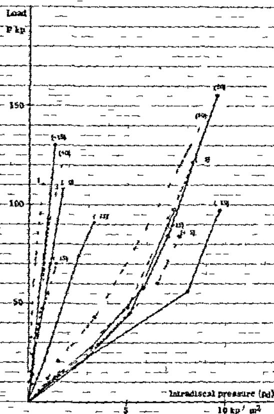


Fig. 74
N. 29 L3–L4–L5
Intradiscal pressure (pd) of one specimen including two discs
Disc L3–L4 tested intact O——O
and after fusion ●——●
Disc L4–L5 tested intact O- -O
and after fusion ● - -●

L3 L4 and L5 with the two intermediate discs The specimen was arranged and fastened in the loading apparatus in the usual way It was loaded first as an intact specimen with the vertical load applied centrally and with positive and negative eccentricities A plastic cast was then applied

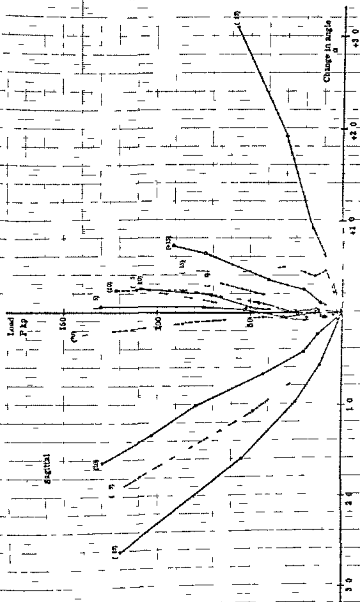


Fig 15
Nr 29
L3–L4–L5

which fused the spinous processes, laminae and intervertebral joints of the three vertebrae in a single block The loading series was then repeated as for the intact specimen As a limited number of pressure and motion gauges were available, consequently the measurements were made first on the lower disc and then repeated with the gauges applied to the upper disc.

The results for intradiscal pressure in each disc before and after fusion are presented in Fig 74 and for the change in angle in Fig 75 The eccentricity was measured in millimeters positively and negatively from the frontal plane through points 2 and 4 on the lowermost (fused) vertebral body The unloaded specimen displayed a slight lordosis and was fused in such a way that central loading over the disc L4 — L5 gave a negative eccentricity for the disc L3 — L4 The changes of angle in the two discs and the fact that the two uppermost vertebrae could become horizontally displaced caused the specimen to buckle so that the middle vertebra (L4) was displaced horizontally against the direction of rotation As a result, the lower disc was subjected to less eccentricity than the one above This is reflected in both the intradiscal pressure and the change of angle, both of which are greater for the upper than the lower disc at both positive and negative eccentricities Otherwise, however, the changes in each interspace are entirely in line with those observed in specimens comprising two vertebrae only and the intermediate disc

Specimen no 32 came from a five-year old child who had died after a skull injury The specimen comprised the vertebrae L2 — L5 with the three intermediate discs It could not be fixed satisfactorily to the sacrum alone so half of the body of L5 had to be included in the casting to the loading apparatus The vertical frontal plane through points 2 and 4 on the body of L4 was taken as the zero plane for eccentricity The specimen was so small and the vertebral bodies so low that only one serie of makers was placed in each vertebra No direct measurements were made of the deformation in the vertebral bodies The angles given were measured between the makers on the vertebral body (formula 2b) It should be noted however that comparisons with calculations of the angle bet ween points 1 and 5 (formula 2a) reveal differences of almost 1° which are thus ascribable to deformation in the bone during eccentric loading With this specimen the gauges had to be moved between three discs consequently the loading series had to be repeated three times on the intact specimen and three times after fusion (type 2) of the vertebrae L3 and L4 The results for intradiscal pressure and change of angle are given in Tables 10 and 11 With this specimen too, it should be noted that the eccentricity is not identical for all three discs during each loading series Counter

Table 10

N 32
L2-L3-L4-L5
Fusion Type 2
Sagittal

Intradiscal pressure pd kp/cm² in a specimen including three discs tested intact (figures in brackets) and after fusion of the intermediate segment

Load kp/cm	Disc level	Eccentricity (mm) of the load						Mean
		—12	—8	—4	0	+2	+4	
1	L2—L3	(1 3)	(1 7)	(1 8)	(1 5)	(1 3)	(—)	(1 5)
		1 8	2 2	1 6	1 9	1 9	1 8	1 9
	L3—L4	(1 8)	(2 1)	(1 8)	(2 0)	(1 8)	(2 1)	(1 9)
		1 3	1 3	1 4	1 1	1 2	1 3	1 3
	L4—L5	(1 4)	(1 4)	(1 5)	(1 6)	(1 2)	(1 4)	(1 4)
		1 4	1 5	1 5	1 5	1 5	1 7	1 5
2	L2—L3	(2 9)	(3 6)	(3 7)	(3 1)	(2 9)	(—)	(3 3)
		3 6	4 2	3 1	3 8	3 7	2 7	3 5
	L3—L4	(3 8)	(4 1)	(3 7)	(3 9)	(3 7)	(3 9)	(3 9)
		2 6	2 6	2 8	2 6	2 7	2 8	2 7
	L4—L5	(2 8)	(2 9)	(3 0)	(2 9)	(2 7)	(2 9)	(2 9)
		2 8	3 0	3 0	3 1	3 1	3 1	3 0
3	L2—L3	(4 6)	(4 9)	(5 3)	(4 6)	(4 6)	(—)	(4 8)
		5 2	5 9	4 6	5 6	5 3	4 1	5 1
	L3—L4	(5 9)	(6 2)	(5 6)	(5 4)	(5 5)	(5 5)	(5 7)
		4 0	3 8	4 2	4 2	4 5	4 3	4 2
	L4—L5	(4 1)	(4 3)	(4 2)	(4 3)	(4 1)	(4 2)	(4 2)
		4 2	4 5	4 5	4 6	4 7	4 5	4 5
4	L2—L3	(6 3)	(6 2)	(6 7)	(6 2)	(6 1)	(—)	(6 3)
		6 6	7 5	6 0	7 2	7 0	6 9	6 9
	L3—L4	(7 7)	(7 7)	(7 1)	(6 3)	(7 0)	(6 9)	(7 1)
		5 4	5 1	5 5	5 7	6 4	6 0	5 7
	L4—L5	(5 4)	(5 6)	(5 5)	(5 6)	(5 4)	(—)	(5 5)
		5 5	5 8	5 9	6 1	6 1	5 7	5 9
5	L2—L3	(7 6)	(7 5)	(7 5)	(7 2)	(7 3)	(—)	(7 4)
		7 8	8 9	7 0	7 9	8 5	—	8 1
	L3—L4	(8 6)	(8 9)	(8 3)	(7 2)	(8 1)	(—)	(8 6)
		6 7	6 7	7 0	7 2	7 7	—	7 1
	L4—L5	(6 6)	(6 8)	(6 9)	(6 9)	(6 9)	(—)	(6 8)
		6 9	7 1	7 3	7 4	7 3	—	7 2
Mean	L2—L3	(4 5)	(4 8)	(5 0)	(4 5)	(4 4)	(—)	(4 7)
		5 0	5 7	4 5	5 3	5 3	3 9	5 1
	L3—L4	(5 6)	(5 8)	(5 3)	(5 0)	(5 2)	(4 6)	(5 4)
		4 0	3 9	4 2	4 2	4 5	3 8	4 2
	L4—L5	(4 1)	(4 2)	(4 2)	(4 3)	(4 1)	(2 8)	(4 2)
		4 2	4 4	4 4	4 5	4 5	3 8	4 4

Table 11

Nr 32
L2–L3–L4–L5
Fusion Type 2
Sagittal

Change of angle (α°) in a specimen including three discs tested intact (figures in brackets) and after fusion of the intermediate segment

Load kp/cm²	Disc-level	Eccentricity (mm) of the load				
		—12	—8	—4	±0	+2
1	L2—L3	(—0.66)	(—0.50)	(—0.07)	(+0.45)	(+0.87)
		—0.72	—1.04	—0.84	—1.75	—2.40
	L3—L4	(—0.31)	(—1.45)	(—1.48)	(—1.60)	(—1.19)
		—0.17	—0.02	—0.05	+0.05	+0.02
	L4—L5	(—0.71)	(—0.56)	(—1.18)	(—0.17)	(—0.10)
		—0.19	—0.10	—0.13	—0.19	—0.20
2	L2—L3	(—1.16)	(—0.98)	(—0.17)	(+0.89)	(+1.16)
		—1.43	—1.87	—1.68	—3.38	—3.40
	L3—L4	(—0.91)	(—2.52)	(—2.31)	(—2.21)	(—2.00)
		—0.27	—0.05	—0.05	+0.06	+0.07
	L4—L5	(—1.43)	(—1.11)	(—1.64)	(—0.39)	(—0.13)
		—0.39	—0.18	—0.23	—0.30	—0.40
3	L2—L3	(—1.52)	(—1.20)	(—0.33)	(+1.28)	(+1.66)
		—2.04	—2.24	—2.25	—3.46	—3.26
	L3—L4	(—1.76)	(—2.89)	(—2.62)	(—2.35)	(—2.13)
		—0.28	—0.08	—0.06	+0.07	+0.14
	L4—L5	(—1.59)	(—1.24)	(—1.59)	(—0.70)	(—0.37)
		—0.62	—0.26	—0.28	—0.41	—0.57
4	L2—L3	(—1.88)	(—1.42)	(—0.45)	(+1.68)	(+2.51)
		—2.52	—2.61	—2.51	—3.52	—
	L3—L4	(—2.47)	(—3.21)	(—2.94)	(—2.59)	(—2
		—0.29	—0.12	—0.08	+0.11	+
	L4—L5	(—0.71)	(—1.27)	(—1.62)	(—1.09)	(
		—0.85	—0.41	—0.29	—0.50	
5	L2—L3	(—2.25)	(—1.64)	(—0.49)	(+2.10)	
		—2.80	—2.85	—2.97	—3.41	
	L3—L4	(—2.86)	(—3.49)	(—3.24)	(—2.73)	
		—0.36	—0.14	—0.14	+0.1	
	L4—L5	(—1.83)	(—1.40)	(—1.66)	(—1	
		—1.00	—0.56	(—0.29)	—0	

balancing in the discs by means of horizontal displacement is still more noticeable than in the previous specimen owing to the larger number of motion segments The initial position of the specimen ("own shape Fick 1904) is shown in Fig 76 The automatic balancing in the specimen is illustrated schematically for the intact specimen (Fig 77 *a*) and after fusion (Fig 77 *b*) It will be seen that although changes of angle do occur positively and negatively after fusion of the interspace L3—L4 they are very small At zero and + 2 mm eccentricities the disc L3—L4 rotated in a negative direction before fusion but in a positive afterwards This change of angle was accompanied in the disc above by a relatively large positive change of angle, in the intact specimen to a relatively large negative change after fusion of the middle segment The lowermost disc displayed negative rotation throughout, but this was considerably smaller after fusion of the middle segment Fusion thus resulted in a quite different balancing of the complete specimen owing to the fact that the scope for horizontal displacement was largely eliminated in the fused segment



Fig 76 *Lateral X ray view of spec nr 32 L2—L5 (cf Fig 77)*

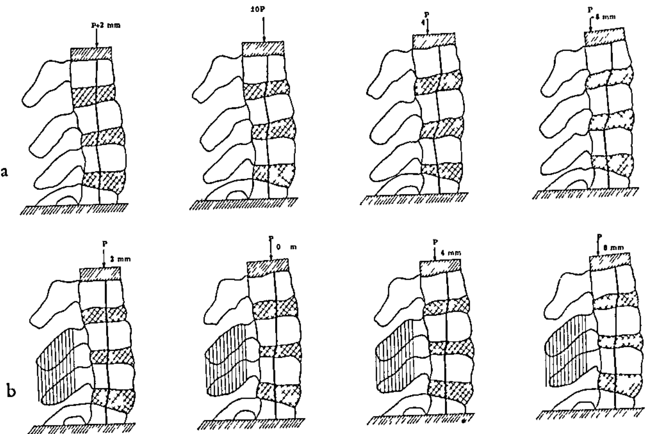


Fig 77
Scheme of horizontal sh ft (buckl ng) In a specimen (Nr 32) incl di g th ee d scs at var o s appl cat on of a con tant load (5 kp/cm) tested ( ) intact and with the intermediat di c fused (b)

V Summary and conclusions

Low back pain has frequently been interpreted as a mechanical disturbance based on structural changes in one or several intervertebral discs. The selection of suitable cases for fusion on the basis of this assumption has failed however to give uniform results. In mechanical terms the aim of fusion is to prevent motion and to relieve the load on the intervertebral disc. To achieve this various surgical procedures have been developed approaching different parts of the vertebrae.

In order to elucidate the mechanical efficiency of different types of posterior lumbar fusion experiments were made in the present study on autopsy specimens. A method was developed for fusing the posterior elements of two vertebrae with plastics in such a way as to preclude both slipping at the junction between bone and plastics and any appreciable deformation in the plastic cast itself. Precautions were taken to avoid desiccation during the experiments as well as an excessive temperature during hardening of the cast. Three types of fusion were simulated. Type 1, involving only the spinous process, corresponds to Albee's graft. Type 2 includes the laminae and intervertebral joints (a combination of Albee's and Hibbs fusion) while type 3 includes the transverse processes as well. Using a compression apparatus the specimen was subjected to vertical loads corresponding to those incurred in the upright body posture and in bending forwards, backwards and to the sides. The load was applied in such a way that its position in relation to the centre of the disc could be measured and varied. The lower vertebral body was firmly fixed in the loading apparatus while the upper part of the specimen was free to move horizontally and vertically in the plane being studied and thereby adjust its position to the load applied. Deformations and displacements both vertical and horizontal in the disc and vertebral body were measured with extensometers applied between markers on the specimen itself. This meant that no external reference points were necessary and separate measurements could be made of different parts of the vertebra and disc giving greater accuracy than could be achieved with previous methods. Vertical deformations in the segment were measured between the spinous processes along the anterior surface and both sides of the disc as well as

between two markers on the upper vertebral body For investigations in the sagittal plane, horizontal displacement was measured on the upper spinous process and on the anterior margins of both vertebrae The pressure in the centre of the disc was also measured at the same time The vertical load was increased by stages and recorded, together with the corresponding deformations, via an electric monitor and recorder The specimens were subjected to series of loading with varying eccentricity in the frontal and sagittal planes, both in an intact state and after fusion, as well as after excision of the disc from the fused specimen

A total of 71 specimens were studied, from 38 autopsies Some 1500 loading sequences were carried out on these

The tested discs were examined macroscopically and classified into 4 degrees of degeneration Groups 0 and 1 were regarded as normal discs and groups 2 and 3 as discs with an increasing degree of degeneration Fusion was performed on 33 specimens and the remainder were investigated for the stabilizing effect of ligaments and intervertebral joints or used for other special studies

From the primary data calculations were made of the load per unit area, the relative (percentage) deformation of the disc at each measuring point as well as the change of angle in the sagittal and frontal planes Tables were compiled for each loading sequence, giving the primary data and calculated values, and graphs were drawn for each parameter

The investigation was arranged so that each specimen served as its own control There were considerable differences between the various specimens, particularly in their geometric properties (initial angle height and surface of the disc) By using relative figures for the size and location of the load, for the deformations measured and for intradiscal pressure, it was nevertheless possible to combine the results and report them in diagram form as means with their standard deviation Special aspects could be illustrated with graphs from single specimens

The geometric centre of the disc was defined as the mid point of the sagittal diameter measured between the tangents to the ventral and dorsal peripheries of the horizontal cross section If a vertical point source load is moved along the sagittal diameter, a point — characteristic of each disc — will be reached at which the height of the disc is diminished equally all round its periphery This point (termed the balanced position of the load) lies at an average 2 5 mm dorsal to the geometric centre of the disc but is here equated with this for the sake of convenience Central loading thus means that the disc is compressed without any change of angle in either the sagittal or the frontal plane As the central load increases the disc becomes gradually more rigid, indicating its viscous

nature For all specimens the compression of the disc amounted to only 3 per cent with an external load of 5 kp/cm disc area (a total load of about 100 kp) Measurable deformation of the vertebral body starts at about this load as the rigidity of the disc increases so does the deformation of the vertebral body Previous investigations with external reference points have in actual fact produced a combination of these two curves for disc specimens, plus a large initial deformation arising from adaptation of the specimen to the loading surfaces The deformation curve for disc and vertebral body is indicative of an excellent balance between the two different materials comprising a segment At relatively small loads energy is absorbed in the disc, but as the load increases, the energy is gradually taken up by the vertebral body until ultimately the end plate fractures

Degenerated discs show a larger vertical deformation than normal ones at least up to loads of 100 — 120 kp The difference is small in absolute figures but statistically significant

Eccentric loading involves a vertical force acting at the centre of the disc and a moment both of which elicit counterforces until a new balance is set up through a change in the shape of the disc and in the angle between the vertebrae For the same moment and the same vertical load the disc s resistance to a change of angle is greatest in extension less in lateral flexion and least in flexion A load of 60—80 kp acting through its resultant at half the radius of the disc gives extension of approximately 0 02 radians (1 1°) but flexion of approximately 0 04 radians (2 3°) The change of angle is not proportional to the moment but diminishes as this increases Similarly for the same moment an increasing vertical load component results in a diminishing tendency to change of angle Conversely this implies that the spinal musculature can straighten the spine from a posture of flexion with a smaller moment than that achieved by the superimposed body weight In this respect the disc serves as an energy saving device in the construction of the spine

In keeping with the greater vertical deformation of degenerated discs these also display less resistance than normal discs to flexion On the other hand no instability in the form of increased horizontal displacement was detected in the degenerated discs studied in this investigation The horizontal component in ventrodorsal and lateral motion seldom exceeded ± 1 mm and was never more than ± 2 mm The picture might differ if larger levers were used for the load

On excision of the intervertebral joints and severance of the ligaments between the posterior elements a slight increase in the dorsal height of the disc was observed when the ligamentum flavum (interarcuate ligament)

was cut, demonstrating that this ligament produces a small pre-load on the disc, the significance of which is eliminated upon vertical loading. The ligamentum flavum is probably not an essential factor in the mechanics of the spine, its function being rather to give the vertebral canal a smooth, dorsal covering in all positions of the spine. The intervertebral joints are so designed that they resist torsion in the segment, but, in the present study and for the range of movement tested, they did not impede either extension or lateral flexion.

Fusion of the posterior elements of the vertebrae gives rise to a force acting cranially in the segment and a moment directed dorsally. The size of this moment is conditioned by the physical properties and dimensions of the fusion material and by the leverage of the vertical load. In the experimental fusion the plastic cast was dimensioned so as to give no appreciable deformation. In fused specimens with the disc excised — loaded as a cantilever — the posterior elements fractured, immediately in front of the fusion, i.e. for type 1 through the base of the spinous process, for type 2 through the laminae or articular processes and for type 3 through the pedicles. The bending moment at fracture was 128 ± 37 kp for type 1 fusion, 181 ± 22 kp for type 2 fusion, and 252 ± 28 kp for type 3 fusion (mean 185 ± 18 kp). The mean load at fracture was 70 kp applied 5 mm dorsal to the specimen's centre. It seems unlikely that even the strongest posterior fusion (combining Albee's, Hibbs' and transverse fusion) in vivo would be able to resist the force of superimposed body weight without anterior support unless all forward bending is restricted. If the strength of the bone is impaired, even the erect posture should be deleterious.

The specimens fractured at a mean vertical displacement at the anterior border of the upper vertebra of 4 mm and at the posterior border of 2 mm. This displacement is much more than is possible with the intervening disc supporting the vertebral body. During loading of fused specimens with the disc excised, the greatest concentration of stress is immediately in front of the fusion and this is where the fracture occurs. The same load which fractures specimens from which the disc has been removed produces a vertical displacement at the anterior border of less than 1 mm in specimens with the disc retained; this corresponds to a displacement at the posterior border of less than 0.4 mm. Thus, the strain in fused specimens supported by the discs is less than 25 per cent compared to fused specimens with the discs excised.

As the disc's resistance to deformation increases with the load, the percentage increase of strain in the fusion diminishes, at the same time as it grows in the disc. When maximal deformation of the disc has been reached,

the vertebra may be regarded as a beam supported at both ends and loaded at the anterior support The strain in the fusion and the posterior elements will then increase only to the extent that the vertebral body is compressed. In intact specimens a load applied in front of the centre of the disc produces compression in the anterior and tension in the posterior parts of this, and vice versa for loading dorsally of the centre This tendency naturally persists even after fusion but for the loads used the bone's resistance to bending was sufficient to entirely prevent tension forces in the anterior part of the disc the posterior part of the annulus however was subjected to tension if the unsupported part of the vertebra was sufficiently long i e in type 1 fusion In theory the same effect should be produced at a larger moment in type 3 fusion but in practice the vertebral body would probably fracture first

With the disc retained fusion thus results in a lifting force in the posterior elements and a dorsally directed moment in this way the angle of the segment is largely prevented from changing The strain in the posterior elements and in the fusion is relatively small but this suggests that, in spite of the fusion the stability of the system is largely determined by the ability of the disc to resist tensile and compressive forces. The poorer the support which the disc can offer the greater the strain on the fusion and the weaker its stabilizing effect

Further, this means that to be mechanically efficient, a fusion requires good strength in both bone and disc A spine weakened by infectious processes, tumors, osteoporosis or recent fractures seems hardly suitable mechanically for a posterior fusion In theory a degenerated disc supports fusion less well than a healthy one The differences in behaviour observed in the present study between healthy and degenerated discs were relatively small. If the mass of the disc however is reduced through partial excision or through lesion of the endplates there is less chance of achieving a stable posterior fusion

Fusion has the effect of distributing the vertical load over the segment in such a way that changes of angle are considerably reduced. The pressure is thereby distributed evenly over the entire disc. The intradiscal pressure measured at the centre of the disc is appreciably reduced when loads are applied near the fusion From there it rises steadily however and for positive moments (flexion) tends to increase more rapidly than at corresponding loads without fusion suggesting that moments larger than those employed in the present study would tend to produce a greater strain in the centre of the disc after fusion than before

In the case of specimens comprising several segments, the effect of the fusion is noticeable even in adjacent segments These have to balance the

applied vertical loads in quite a different way after fusion This can mean that a load which gave a change of angle in a negative direction before fusion produces a positive change in the free segments after fusion Depending upon the application of the load — the moment — fusion can thus extert a stabilizing effect on the free segments or an increased strain as well

Although the conclusions which can be drawn from the results are naturally limited by the nature of the material and the methods used, they may provide a basis for clinical interpretations

These experimental results indicate that a posterior fusion obviously provides a stabilizing effect on the involved segment. It is not possible to obtain a complete obstruction of all motion between vertebrae, even if most parts of the posterior elements are fused The effect is dependent on the forces involved A posterior load resultant is counteracted by the fusion whereas, a more anterior load will tend to put increasing strain on the disc. In the most extreme cases the strain on the disc may be even greater after than before a posterior fusion

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